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Sandboxing remote code execution in the distributed system RCE

by
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Statutory declaration

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Declaration of Authorship

I hereby declare that the thesis submitted is my own unaided work. All direct or indirect sources used are acknowledged as references.

This paper was not previously presented to another examination board and has not been published.

Signature *City and date*

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List of Abbreviations

ABI	**A**pplication **B**inary **I**nterface
ACL	**A**ccess **C**ontrol **L**ist
API	**A**pplication **P**rogramming **I**nterface
CPACS	**C**ommon **P**arametric **A**ircraft **C**onfiguration **S**cheme
CPAS	**C**onditional **P**ermission **A**dmin **S**ervice
DLR	**D**eutsches Zentrum für **L**uft- und **R**aumfahrtdro
EPL	**E**clipse **P**ublic **L**icense
IDE	**I**ntegrated **d**evelopment **e**nvironment
ISA	**I**nstruction **S**et **A**rchitecture
JDK	**J**ava **D**evelopment **K**it
JVM	**J**ava **V**irtual **M**achine
Malware	**Mal**icious Soft**ware**
OS	**O**perating **S**ystem
OSGi	**O**pen **S**ervices **G**ateway **i**nitiative
PAS	**P**ermission **A**dmin **S**ervice
RCE	**R**emote **C**omponent **E**nvironment
RCP	Eclipse **R**ich **C**lient **P**latform
SWT	**S**tandard **W**idget **T**oolkit
VM	**V**irtual **M**achine

1 Introduction

Scientists and engineers are using a distributed system **R**emote **C**omponent **E**nvironment (RCE) to design and simulate complex systems like airplanes, ships and satellites. During the simulation, RCE executes local and remote code. Remote code is classified as untrusted code. The execution of remote code comprises potential security risks for the host system of RCE. Additionally, RCE provides full access to system resources. The objective of this thesis is to implement a sandbox prototype to reduce the vulnerability of RCE during the execution of remote code.

1.1 Sandboxing

Software systems execute source code. Source code is classified as local or remote code depending on the level of trust. Local code is developed by a known and trusted developer. Remote code is provide by either a known or unknown developer on a network such as the internet. For that reason, remote code is regarded with suspicion since the source of the remote code is untrusted, and therefore could be malicious [GMPS97].

The motive to download and execute remote code is to add new or additional functionality to a software system. The most common type of software systems that rely on remote code execution are web browsers. The programming language Java Script is implemented on many web pages to provide additional functionality for the user. A web page accessed from the internet downloads and executes Java Script within the Browser. Applications, better known as Apps, which are developed by third parties for an mobile operating system. The execution of remote code is an important aspect of software systems, however, it involves potential security risks.

A comprised system that manipulates or spies on personal data is a possible consequence of executing remote code. Hence, it can be considered malicious, intentionally or unintentionally [AS11]. For example, data can be manipulated by unintentional programming mistakes. Ransomware is a recent intentional threat spreading through Word or PDF files that attempts to encrypt all data on a computer. Therefore, remote code should only get limited permissions to access resources, such as files and networks.

Researchers became interested in developing and improving isolation methods to reduce the likelihood of attacks caused by executing remote code. An important approach in this spirit is called Sandboxing. A sandbox creates an isolated environment within an operating system. It controls and limits the access of remote code to resources outside the isolated environment, thus protecting the operating system from any unexpected and undesired effects of remote code running within the sandbox. Due to the rapid development of the internet, sandboxing is an essential method to improve the security of software systems. Sandboxing is used in various relevant products such as the Chrome Browser, the Android **O**perating **S**ystem (OS) and the Adobe Reader [MSCS16].

Researchers who investigate in sandboxing put a strong focus on security and engineering aspects of sandboxes. However, the usability aspect and the consequences of sandboxing for the user are mostly disregarded [MSCS16]. Therefore, it is worthwhile to consider the implementation of sandboxing in a software application and to identify the resulting consequences for the user experience.

The Eclipse-based application RCE is an open source framework for scientists and engineers to design and simulate complex systems like airplanes and satellites. The two main feature are that RCE is developed as a distributed environment and supports a reusable component-based approach. Different users can work together on a complex system via a network of RCE instances. RCE has full access to system resources which makes the system vulnerable to

malicious code executed within RCE. Therefore, isolation techniques are interesting for RCE to restrict the access of resources and reduce the system vulnerability.

1.2 Constrained execution

RCE grants permission to access system resources during the simulation of a complex system. A simulation of complex systems consists of local and remote components. Therefore, RCE is extremely vulnerable to malicious code contained in a remote component. The execution of a malicious remote component may harm or manipulate the system. It remains to be examined whether there is an effective method to secure RCE. Isolation techniques are considered to constrain remote code execution. Among the isolation techniques, sandboxing allows to control and limit permissions granted to access any system resource.

The objective of this thesis is to design and implement a sandbox prototype to secure RCE. Existing sandbox models, which are available for implementing the prototype, are analyzed and described and elements of RCE with access to system resource are identified to support the implementation. Additionally, the effects that the sandbox prototype has on both security and the user experience through the RCE application are discussed and reflected.

2 Isolation techniques for software systems

Computers are used for various functions like video editing, programming and web surfing. Isolation provides a protection barrier in a computer system to prevent functions from disturbing each other. The isolation of computers is reduced by connecting computers to a network or performing several functions on a single computer. Vulnerabilities of a computer system can be exploited and the whole system can be compromised with missing isolation. Therefore, the general purpose of isolation techniques is to protect a computer system against exploiting vulnerabilities [VN10].

Isolation techniques are essential in computer security and have been introduced in 1972 by James Anderson, before the arrival of the internet and the wide distribution of personal computer. At that time, isolation techniques were considered, because security and privacy problems rose with the occurrence of computer systems capable of sharing resources. Users are provided with features to share operations and data with other users. Those features are extended to computer networks. Security issues were caused by concurrent execution of processes and storing sensible data in the same memory regardless of the different user permissions. The execution of programs should be controlled to ensure a secure environment for sharing system resources [And72].

In recent years, the need for isolation techniques increases, due to the constant growth of network-compatible devices such as laptops, desktop computers and mobile devices. Furthermore, the rapid development and the increasing importance of the internet increased the demand for isolation techniques. The logic of computer security is subject to constant changes, because of the combination of these devices with the internet and the continuous distribution of new devices and the internet [VN10].

The increasing importance of network-compatible devices makes new types of attacks possible and increases them. **Mal**icious Soft**ware** (Malware) is the umbrella term for various attacks such as worms, viruses, ransomware and Trojan horses. Malware infects one part of the computer system and tries to gain access to the rest of the system or even to the network [VN10]. Isolation techniques have the potential to limit or even avoid the effect caused by a Malware attack. The usage of isolation techniques has evolved to be used by software engineers not only for security in software systems, but also for modular design of software components and to isolate the failures of components [VN10].

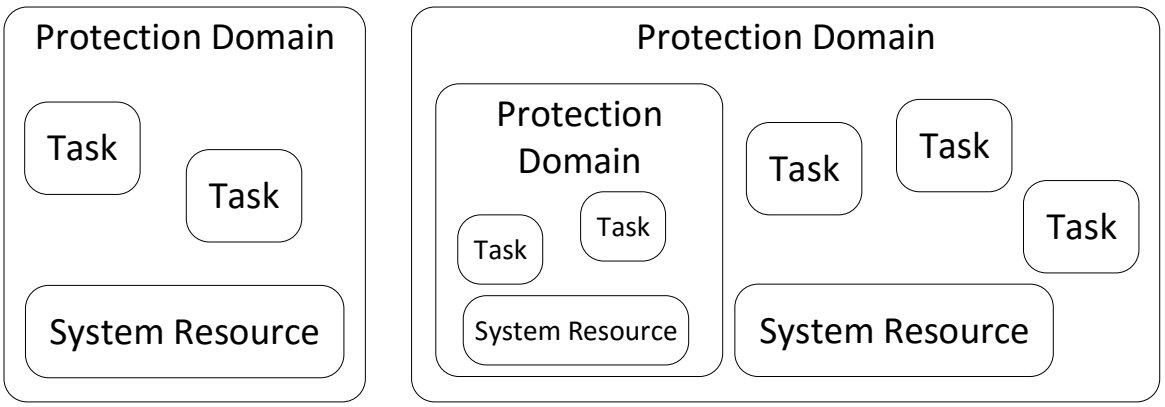

Figure 1: Generic isolation model [VN10]

Figure 1 visualizes a generic model of isolation in a computer system. The model consist of Tasks, System Resources and Protection Domains. Every type of software using system resources to execute an individual function falls into the abstract description of a task. Software such as a web browser or a text editor are examples for tasks. The system comprises a set of resources such as file system, network or CPU and a system resource is at least one element of the set. Tasks share the resources during the execution of their function. Resource sharing raises security issues. However, it is essential for an efficient usage of the resources. A protection domain encapsulates the system resources and tasks. It implements a protection policy by using an isolation technique. Furthermore, the model permits protection domains to be within other protection domains [VN10].

Isolation techniques for software systems are known as **V**irtual **M**achine (VM)-based isolation, sandbox-based isolation, language-based isolation, OS-kernel-based isolation, hardware-based isolation and physical isolation. VM-based isolation can be divided into multiple approaches such as Hypervisor-based and Container-based virtualization. The sandbox isolation has three common approaches referred to as **I**nstruction **S**et **A**rchitecture (ISA)-based, **A**pplication **B**inary **I**nterface (ABI)-based and **A**ccess **C**ontrol **L**ist (ACL)-based [VN10]. The following sections describe and compare the three most common used isolation techniques in more detail: Hypervisor-based, Container-based and Sandbox-based.

2.1 Virtual Machine-based isolation

A **V**irtual **M**achine is a software abstraction of a physical machine and it provides a virtual platform for executing tasks. The virtual platform can either execute an entire operating system or customized processes which differ based on the abstraction level of the virtual machine [VN10]. Multiple VMs can be installed and executed on the same hardware. VM-based isolation is referred to as virtualization technology and the usage has increased sharply in recent years. The requirements for virtualization solutions are efficiency, scaling and secure user environments. Different approaches emerge in the market of virtualization technologies. Container-based and hypervisor-based isolation are established as core technologies. Other approaches are known as process-based, hosted-based and hardware-based isolation [Bui15, VN10].

Software engineers are using VM technologies to gain several benefits. The benefits of VM are isolation, hardware independence and increased scalability [MKK15]. Multiple VMs installed on the same hardware are isolated which increase the overall security of the guest and host system. Once a guest system is compromised or produces an error the isolation prevents other guests and even the host system to be affected [SN05].

Various technologies make use of VM ranging from desktop and server virtualization, programming languages to services offered in the cloud. Desktop virtualization enables to run multiple **O**perating **S**ystem on one computer. It establishes support for applications which run only within specific OS. Server virtualization works similar and lets numerous virtual systems run on one server. The virtual systems imitate a physical server. A common business model is to rent the virtual systems in the cloud based on subscription. Amazon EC2, Rackspace and DreamHost are just a few providers of virtual servers in the cloud [Bui15].

Virtual servers are a great example for isolation and scaling. In terms of isolation, virtual servers can be used to execute one specific task using related data. Tasks running on a server are not allowed to manipulate the data of other servers and therefore, increase the security. Virtual servers are easily scalable to increase or decrease capacities depending on the number of requests and exchanged data [MKK15].

The programming language Java uses a process virtual machine as execution environment of Java applications [VN10]. The virtual machine is called **J**ava **V**irtual **M**achine (JVM). At the start of a Java application, an instance of the JVM is initiated and the only purpose is to run the application. Each started application is executed in its own JVM instance. The instance lives until the application is completed. The JVMs benefit is its platform independency. Hence, Java applications can be executed on various operating systems which offer an JVM such as Windows, Linux and MacOS [Ven00].

2.1.1 Hypervisor-based isolation

The hypervisor-based isolation technique illustrated in Figure 2 comprises of a Hypervisor engine and **V**irtual **M**achines. The technique creates the isolation at the hardware level [Bui15]. It involves providing virtualized system resources, which result in overhead virtualizing the hardware and providing virtual drivers [MKK15]. The installed VMs run on top of the virtualized system resources.

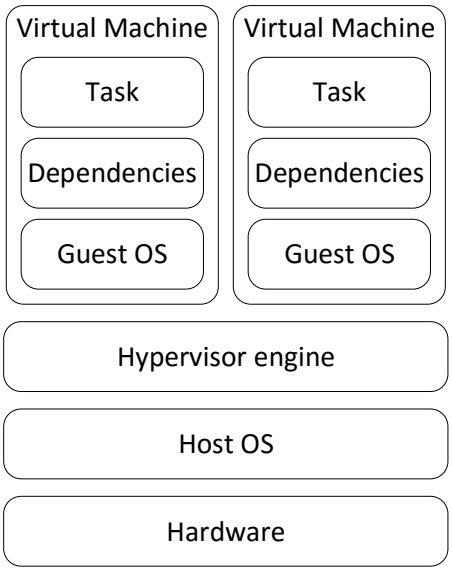

Figure 2: Hypervisor-based Virtualization [Bui15]

A VM contains an entire operating system and essential libraries and provides the platform for performing tasks. The operating system executing the isolation technique is the host OS. A Hypervisor engine operates between the host and the virtual machine referred to as guest system. The hardware resources are split up between all guest systems by the engine. Additionally, the hypervisor installs the virtual machines and controls all access starting from the guest system to the hardware resources. The access control establishes the isolation among all virtual machines. The VM can be implemented in two different approaches. In the pure-isolation approach, the VMs are unable to share resources among each other. On the other hand, the sharing approach allows sharing resources between the VMs [VN10].

The hypervisor approach is used in the professional as well as in the private sector. Virtual machines are useful for individual users in a company network. Each user has its own dedicated virtual machine which allocates relevant resources like computation power, memory and storage. The user is able to log in to the VM at work or remotely. The IT department can be centralized through this approach by offering powerful physical machines to multiple users. It reduces the expenses of installing and setting up individual computers at different locations. Other

operating systems can be executed in virtual environments on one host system, for example Windows can run on MacOS. The user is able to use the full range of applications supported by the host and the guest operating systems. Furthermore, personal and business activities can be separated with the VM approach. VMs find use for daily applications such as browsers and email clients. In the presence of Malware only the VM is affected and the host system remains unharmed [Oli]. It finds application for Malware analysis running suspicious applications within virtual machines and identifying the effects [MSCS16]

VMWare introduced virtualization software reshaping the application areas of virtual machines in 2001. VMWare offers virtualization solutions for desktop and server. Oracle offers VirtualBox a free and open-source virtualization application. It provides features for advanced users who like to implement and use scripts to install virtual machines [Oli].

The isolation between the guest and host system is the benefit of hypervisor-based isolation in terms of security. Damage caused by Malware or a software failure is limited to the VM where it occurred. Therefore, other guest systems or even the host system is unharmed [SN05].

2.1.2 Container-based isolation

The isolation approach known as container-based isolation includes a Container engine and multiple virtual environments called Container. The isolation is at the operating system level to avoid overhead. The host operating system kernel is used for providing the containers and to performs tasks. Containers ship without a guest operating system. Therefore, it is also referred to as a lightweight virtualization approach [Bui15].

The container establishes the protection domain providing resources to execute the tasks. Resources can be either shared by the host or installed within the container. Containers look like normal processes on the host. The container engine is located between the OS and libraries of the host machine. All containers are managed by the engine [Bui15]. The architecture of the container-based isolation is visualized in Figure 3.

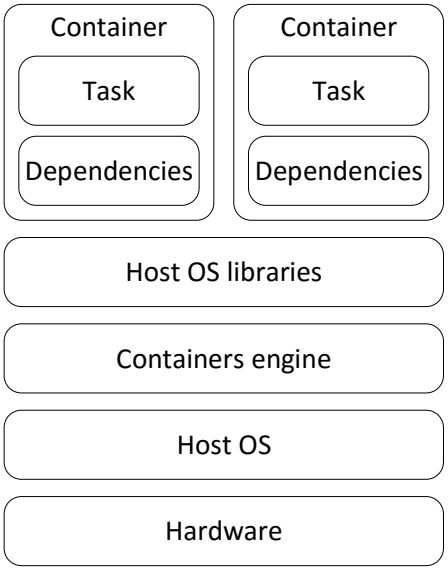

Figure 3: Container-based Virtualization [MKK15]

The advantages of the lightweight approach are the small disk images which make it possible to have a high density of container instances on one host machine. In addition, it offers high performance in virtualization. However, containers are designed for specific operating systems. In other words, a Windows container can not be installed and executed on a Linux host. Another disadvantage is the lack of resource isolation, because the host kernel is visible for each container. It results in security concerns about the container-based approach [MKK15].

A container bundles an application and its dependencies, libraries and other necessary files. It solves the problem to deploy and move software reliable between systems with different software environments. Therefore, the technique is often used for improving the development process including tests and production of an application. The whole container is easily moved from one platform to the other without causing problems [Rub]. Software containers are designed like shipping containers to provide efficiency and to reduce cost just for data center. The fast boot time of containers allow to quickly add more capacities by starting new containers on a server to handle more requests. For example, Google uses a container approach for their search engine handling increases and decreases of occurring search queries [Bab].

The open source container technology Docker has the most success in the sector. It has three main features building, shipping and running of distributed applications. A single application can be wrapped in a lightweight Docker container. It can run virtually on any operating system with an available Docker platform. In addition, the container creation and control can easily and securely be managed by the included interface. Lastly, more lightweight Docker containers can be installed on a single system compared with other virtualization technologies [Bui15].

The container approach provides isolation between all containers deployed on the same host system. The security of the system is enhanced by the host allocating separate memory spaces for each container. Containers are able to run an application undisturbed and the data access of other containers is prevented. However, security concerns remain about the approach, because the operating kernel is exposed to each container deployed on the system [Bab].

2.2 Sandbox-based isolation

Sandbox-based isolation establishes an isolated environment called Sandbox enforcing a Security policy. The security policy clearly states all allowed and forbidden actions to access resources on the host system. For each access, a security check is performed and a decision is made based on the policy [AS11]. It keeps unexpected and undesired effects of malicious tasks within the boundaries of the isolated environment. Therefore, the host system is protected from tasks running within the sandbox. The approach is significant in the development of secure software systems [MSCS16]. Figure 4 shows a general model of the sandbox approach.

In an early state of sandbox-based isolation, it was described as an approach for failure isolation. In addition, sandboxes are implemented for the purpose of stopping the utilization of exploits and ensuring the integrity of the data-flow [MSCS16]. Software engineers use sandboxes in various situations to improve the overall security of software systems. Sandbox-based isolation is often encountered for software components which are used without being verified or trusted. Those components can be tested in a sandbox to identify possible malicious behavior. Software applications can be sandboxed where the data is saved in a virtual storage. The approach is helpful for web browsers. All data collected by the web browser including cookies, browsing history and downloaded files are deleted immediately with terminating the browser. The advantages of this approach are anonymity and privacy for the user. Furthermore, downloaded files which include Malware are deleted without any effect on the system [AS11].

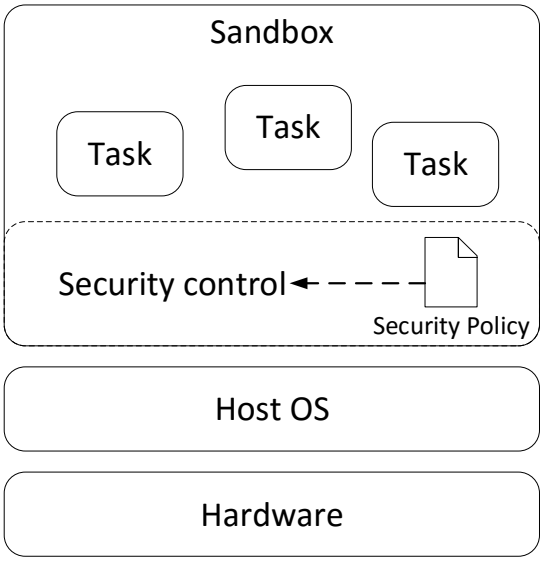

Figure 4: Sandbox-based Isolation

Various relevant software make use of the sandbox approach to improve security by preventing Malware distribution and data manipulation of the system. The browser Google Chrome, the operating system Android and the programming language Java are such examples providing build-in sandbox techniques. Google Chrome displays a web page in a single tab. Each tab represents an independent process which is protected by its own sandbox. In addition to protecting the system against Malware, tabs are not capable of manipulating other tab processes. Malicious code executed in a tab cannot harm the browser or other tabs. The effect is contained and remains only until the tab is closed in the sandbox [BRJI08].

The security of Android is enhanced by executing applications in separate sandboxes. The isolated environments are forbidden to access system resources such as contacts, calender or camera, except user explicitly grants the permissions. Before installing an App, the user is asked to review the required permissions and the installation is only continued when those are accepted. The purpose of the sandbox and permissions is to limit the consequences of bugs and vulnerabilities in Apps. The permission system was updated with Android 6.0 allowing the user to manage the individual permissions at any time [Pro].

The first release of the programming language Java came with a sandbox model implementation. The purpose was to run remote code called Applets in an isolated environment to restrict the access to the system resources. In further releases of Java, the sandbox model was enhanced to provide isolation also for local code and it is customizable for any Java application [GMPS97].

The sandbox approach improves the security of software systems by providing an isolated environment and enforcing a security policy. The security benefits from the isolation and limitation of damage to the system caused by software components executed within the sandbox. An important part is the security policy defining allowed and forbidden actions. Therefore, the sandbox is customizable for the desired system environment based on given requirements [MSCS16].

Classification and comparison of sandbox techniques

A sandbox can use one of three different sandbox techniques. Each technique has its own advantages and disadvantages in preventing a system from attacks. Possible side effects of tasks can be limited at instruction level, operating system level or by performing access controls to critical resources. These techniques correspond to the approaches **I**nstruction **S**et **A**rchitecture (ISA), **A**pplication **B**inary **I**nterface (ABI) and **A**ccess **C**ontrol **L**ist (ACL) [VN10]. The following section describes and compares these three approaches.

Figure 5 illustrates the classification of the previously named sandbox approaches in a computer system. The techniques are located on different layers. Hence, it results in distinct possible uses for each approach.

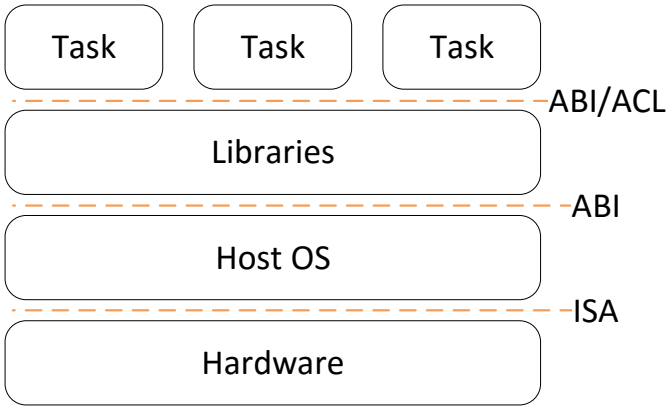

Figure 5: Sandbox techniques [SN05]

Instruction Set Architecture

All sandboxes constraining activities of tasks at instruction level belong to the ISA technique. ISA is based on a well-defined interface between hardware and software as shown in Figure 5. The simplest implementation of the technique is rewriting binary code. Additional commands are inserted before existing code for verification of memory access breaches. Disadvantages of the techniques is the dependency on the computer architecture and the type of command set [VN10].

Application Binary Interface

The interface providing tasks with access to resources of the system is called ABI [SN05]. It is located between the OS and tasks or tasks and the used libraries. A ABI-based sandbox establishes a restricted environment by preventing tasks to call the system. A sandbox of this category confines the effects of tasks by regulating the used ABIs. Configuration files are a common method to determine limited ABIs for the use of tasks [VN10].

Access Control List

A sandbox based on the ACL technique provides certain permissions to restrict tasks via access controls. Permissions are available for system resources such as networks, files and processes. ACL-based is more generic for restricting tasks behavior compared with ABI-based [VN10].

2.3 Comparison of techniques

The comparison explains the differences and similarities of the three isolation techniques described above. The overall comparison of the techniques is visualized in Figure 6. Similar properties of the techniques are symbolized with the dashed boxes. All three approaches create an isolated environment with different impact on containing and securing effects of malicious tasks.

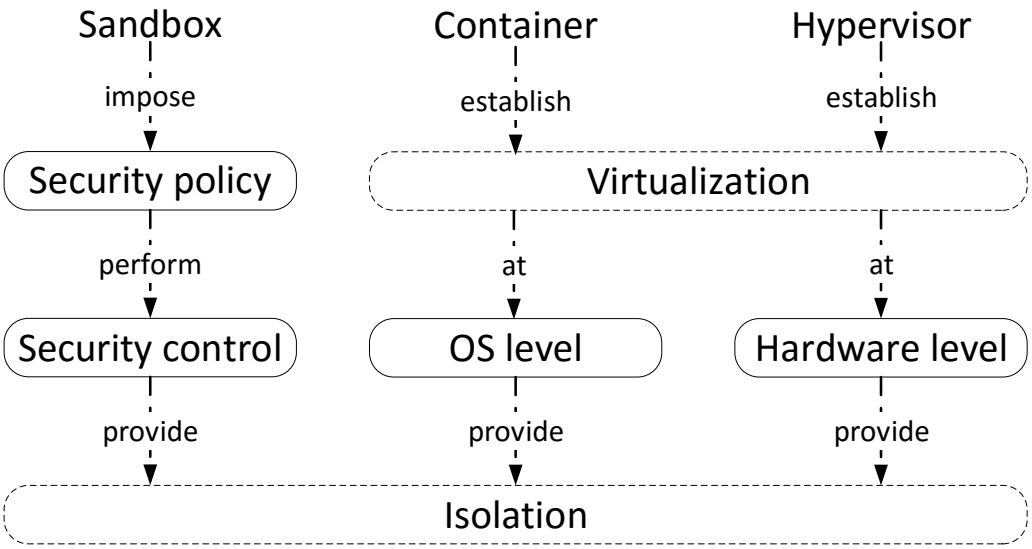

Figure 6: Isolation comparison

Hypervisor and container based isolation

Virtualization is the main purpose of both technologies as shown in figure 6. The technologies establish virtual environments of different scopes. The Table 1 describes the important differences of both techniques. The hypervisor-based performance is slower compared to container-based, because it needs to start a full operating system within the virtual environment. The included guest OS is the reason of the bigger size of VMs. The container approach ships without a separate OS. Therefore, it is often described as the lightweight virtualization approach. The small container size allows to deploy ten times more virtual environments on one host system. However, the container must be from the same type as the host system. For example a Linux container cannot be started on a Windows host which is a disadvantage of the container approach. Hypervisor can deploy virtual machines of different types on several operating systems.

Both technologies provide an isolated environment as visualized in Figure 6. The isolation provided by VMs keeps any unexpected effects within the virtual environment. On the other hand, containers are considered unsecure, because the kernel of the operating system is exposed to all deployed containers. Security vulnerabilities of the kernel might be exploited to access or manipulate a container [Bui15, MKK15, Rub].

	Hypervisor-based	**Container-based**
Virtualization	Hardware level	Operating system level
Virtual environment	Full operating system and applications	Application including dependencies and libraries
Isolation	Between guest and host system	Between other containers
Performance	Slow boot time	Quick boot time
Memory	High usage for each guest OS	Low consumption for using the host OS

Table 1: Hypversior-based vs. Container–based technique

Sandbox and Virtual machine based isolation

Isolation is only the main purpose of the sandbox approach. The sandbox approach imposes a security policy on which the security control makes decisions whether an action is allowed or forbidden. Therefore, the isolated environment is customizable to support the security requirements for a single software system by clearly defining and adjusting the policy.

	Virtual Machine-based	**Sandbox-based**
Isolation through	Virtualization	Security policy and controls
Constrained execution location	Virtual environment	Host system

Table 2: Virtual Machine-based vs. Sandbox-based technique

The virtual machine technique establishes a virtual environment which includes an isolation environment. All effects of tasks are isolated within the boundaries of the virtual environment. Hereby, the isolation enhances the overall security. Nevertheless, the virtual machine techniques comes without an adjustable policy to specify which actions are allowed or forbidden. Virtual machine-based is sometimes referred to as sandbox, because it also provides a constrained execution environment. However, both techniques establishes the constrained execution environment on a different location as shown in Table 2. On the one hand VM-based creates a full virtual machine to execute and constrain tasks. On the other hand sandbox techniques perform and restrict tasks on the host system [VN10].

3 Remote Component Environment

The **D**eutsches Zentrum für **L**uft- und **R**aumfahrt (DLR) began with the development of the RCE framework in 2005. This framework is based on a reusable component-based approach. The increasing complexity of software applications requires reuse of resources to minimize development time and reduce costs.

The main purpose of RCE is to provide an environment for the design, simulation and optimization of complex systems, such as airplanes, satellites or ships. These simulations can theoretically include every possible property of a complex system, such as geometry, aerodynamics and thermal management [SBM+13]. Exemplary projects are explained in section 3.2. Scientists and engineers collaborate and contribute their knowledge to create the simulation of a complex system. Therefore, RCE is designed as a distributed environment. RCE connects various computers into a common project environment. Additionally, it manages the exchange of data between different computers. For this reason, the computations of a simulation can be performed on different computers which contribute to an overall result [SFL+12]. In the further process, the term "user" is used broadly when referring to scientists and engineers. The following section covers important aspects of RCE's architecture which are relevant for the development of the sandbox prototype. In the process, relevant terms of the architecture are described to be used for further explanations.

3.1 Architecture of RCE

The architecture of the RCE framework is laid out to meet the requirements for scientific applications. The basic requirements of the framework are a component-based approach, providing extension features, supporting portability and using open-source licensing. In addition, other essential requirements are important for projects in the field of aeronautics and space. The simulation of complex systems require knowledge and tools of multiple users. For example, these tools can be custom simulations provided by a user. For collaboration purposes, the framework should be designed as distributed software. All scientific data should be recorded in a persistent storage. The framework should provide an environment for connecting components as a workflow and to execute the workflow. Finally, a graphical user interface should allow easy control over RCE for users.

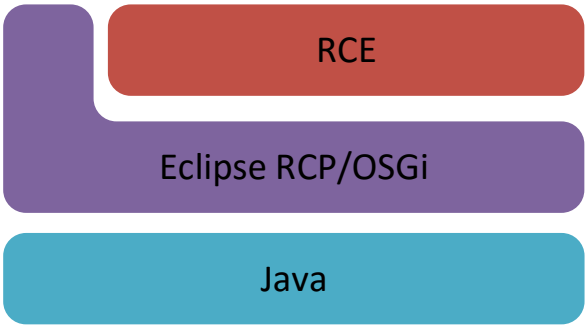

Figure 7: RCE architecture [SFL+12]

Figure 7 shows the overall framework architecture of RCE. Eclipse **R**ich **C**lient **P**latform (RCP) is the foundation of RCEs framework. RCP corresponds with platform independence, supports a component-based approach and is open-source. RCP is an essential framework for the development and research in aerospace and automotive industry. One of many reasons, it is

implemented with Java, the free and modern programming language. Furthermore, RCP is based on an **O**pen **S**ervices **G**ateway **i**nitiative (OSGi) specification which is described in the following subsection. [SFL+12].

3.1.1 OSGi Service Platform and Eclipse Equinox

The OSGi Service Platform provides a modular and dynamic framework for Java. The main component of the OSGi Service Platform is the OSGi Framework as shown in Figure 8. It establishes a container for Bundles and Services. OSGi supports development of extensible and component-based applications. Therefore, it corresponds well with the requirements of RCE. The framework manages the life cycle of required bundles at runtime.

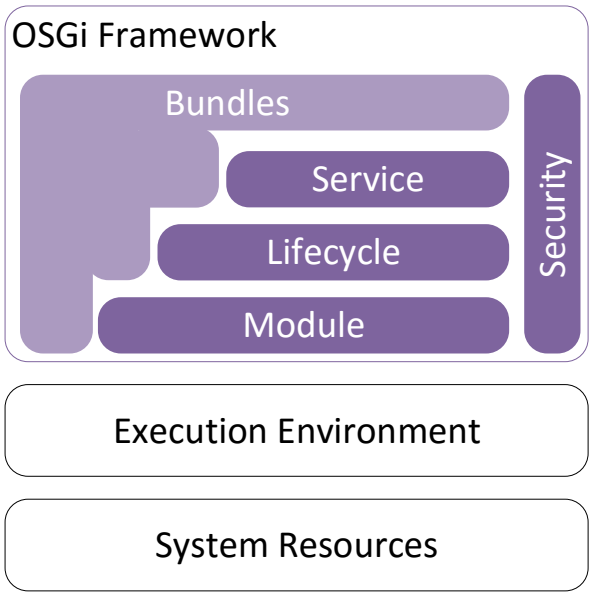

Figure 8: OSGi Framework layer [OSG11]

The OSGi framework is divided into security, module, life-cylce and service layer. Related functionalities are combined in the corresponding layer. Each layer defines important aspects of the bundle concept in OSGi. Therefore, the actual bundles have contact points to all four layers as illustrated in figure 8. The Java security model of JDK 1.2 is the foundation of the OSGi security layer. Configuration of permissions for each bundle and real time updates of permissions are provided as extensions. Two essential services from the security layer are mentioned later in this section. Modularization in OSGi is specified by introducing the bundle concept in the module layer. OSGi enforces strict rules about the visibility of Java packages between bundles. The module layer can be used independent of other layers.

Life-cycle layer defines the states of bundles during their life-cycle in an application. It provides an **A**pplication **P**rogramming **I**nterface (API) for executing bundles and managing their state. A bundle can be in one state at a time such as Start, Stop, Installed and Uninstalled. The life-cycle layer depends on the bundle concept. Therefore, it requires the module layer but the security layer is only optional. The service layer establishes a service model reducing the complexity of the bundle development. A Java interface represents the functionality of a service and is separated from the service implementation. The bundle providing a service contains an interface and an implementation. A Service registry is available centrally for registering and requesting services. Services can be dynamically added and removed by the framework

[OSG11].

Bundle and service concept is introduced for decoupling different modules and to make their functionality reusable. A bundle contains classes and relevant resources. The bundle content is by default invisible for other bundles because of the strict rules enforced by the module layer. Hence, bundles must specify explicitly the content to export and import. Services are available for the whole framework. A service represents a Java object which is published under an interface name. A bundle requesting a service is unaware about the underlying implementation. A mManagement agent is part of the implementation for managing the life cycle of bundles including install, uninstall, start and stop. It self is present as one or multiple bundles known as management bundles. A text-based command console is the simplest implementation of a management agent. However, the OSGi specification does not provide a guideline how to implement a management agent.

OSGi defines five framework services supporting the implementation of a management agent. Two of those implement OSGi-specific services which are unavailable in Java. Firstly, the Package Admin Service provides information about the package dependencies between installed bundles. The information is relevant for a management agent when resolving the dependencies of installed bundles. Secondly, the start and stop order of bundles can be requested and controlled using the Start Level Service.

The other three framework services extend and adapt existing Java implementations for the OSGi framework. The **C**onditional **P**ermission **A**dmin **S**ervice (CPAS) and the **P**ermission **A**dmin **S**ervice (PAS) are extensions of the Java security model. Both belong to the security layer of the OSGi framework. The former service defines a programming interface for creating and managing permission at bundle level. Modified permissions are immediately activated without restarting the bundle or the JVM. In addition, it introduced a condition concept. Certain criteria are evaluated at runtime for granting the permissions. CPAS is an important part of the OSGi security model and it is described in detail in section 4.2.2. PAS also supports the administration of permissions. However, it is superseded by CPAS. The last framework service is called URL Handler Service. It enables bundles to register and remove own URL handler in the system

All RCP-based applications including Eclipse **I**ntegrated **d**evelopment **e**nvironment (IDE) have the same foundation named Eclipse Equinox. At the beginning, RCP implemented a static plug-in infrastructure. New requirements for more complex applications needed a dynamic plug-in infrastructure. The new plug-in infrastructure should enable dynamic behavior for installing and uninstalling plug-ins within RCP. It should be able to add plug-ins at runtime and make them available without application restart. OSGi Service Platform Specification meets exactly the requirements for a dynamical plug-in infrastructure. Therefore, Eclipse Equinox implements the OSGi Service Platform. Eclipse Equinox replaced the old plug-in infrastructure of Eclipse with version 3.0. Plug-ins can be developed excellently by use of the Eclipse IDE provided bundle platform [WHKL08].

Eclipse IDE contains many components such as the graphical user interface, extensible plug-in system and a help component. Other applications also require these basic elements. All these general components of Eclipse IDE were extracted and published as RCP since 2004. Eclipse RCP provides a platform for the development of desktop applications which make use of established graphical components. RCP applications are easily extensible with additional functionalities by plug-ins. Furthermore, it provides the foundation of Eclipse IDE. A RCP application requires at least three components: the Eclipse Core Runtime, **S**tandard **W**idget **T**oolkit (SWT) and JFace. The Eclipse Core Runtime manages the life-cycle of the application and provides features without relation to the user interfaces. SWT provides tools to developers which can create native user interfaces with Java. The user interface elements can be inflated

with data from Java objects by using JFace [Ebe11].

3.1.2 RCE framework

The RCE framework provides a distributed simulation environment for solving research problems. To make the simulation environment available, RCE consists of several software layers illustrated in Figure 9. Furthermore, the layers are the result of the requirements stated in Section 3.1. The layers have dependencies among themselves which are shown in the figure by a layer architecture. A higher layer requires functionalities in form of services of the underlying layers. The GUI layer is connected to all other layers and can use their offered services. Therefore, it is vertical shown alongside the remaining layers.

RCE is an Eclipse RCP application. It can be developed and executed easily with Eclipse IDE. The framework functionalities can be extended by implementing and providing new bundles. An extension may be realized by implementing a services. Additionally, Eclipse RCP provides tools for building native GUIs which is essential for providing the GUI layer in the RCE framework.

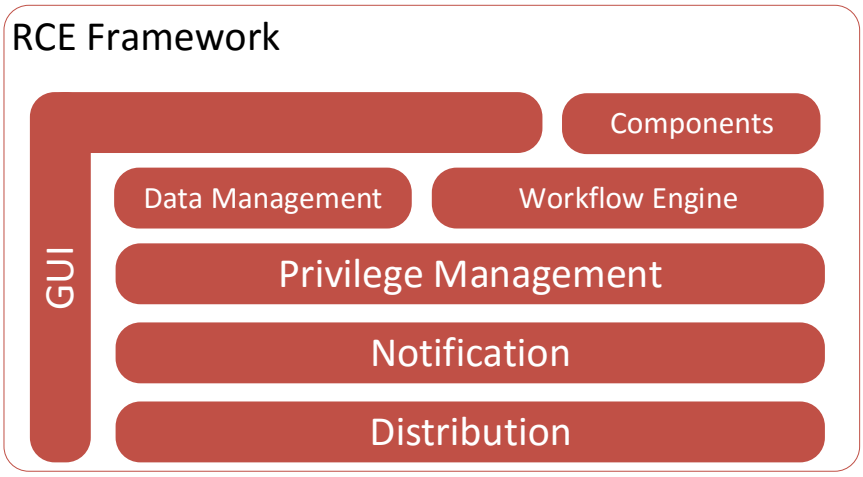

Figure 9: RCE framework layers [SFL+12]

The following software layers of RCE are explained for the ongoing implementation of the sandbox prototype: Workflow Components, Workflow Engine, Data Management and Distribution.

Figure 10 shows the GUI of the RCE application. It divides the user interface into different areas which are similar to the Eclipse IDE. Users familiar with Eclipse IDE quickly learn how to use RCE. The left area shows the project explore. It may contain different projects which comprise of workflows and relevant other resources. The numbered areas are described in the following sections.

Workflow Components

The reusable component-based approach of RCE is provided with the workflow components which are an essential part for solving research problems. These components are available through different sources in RCE. A set of standard components are offered by RCE which perform fundamental functions. Some of the fundamental functionalities are parametric studies, optimizations, input and output of data. The particular functions are mapped to the

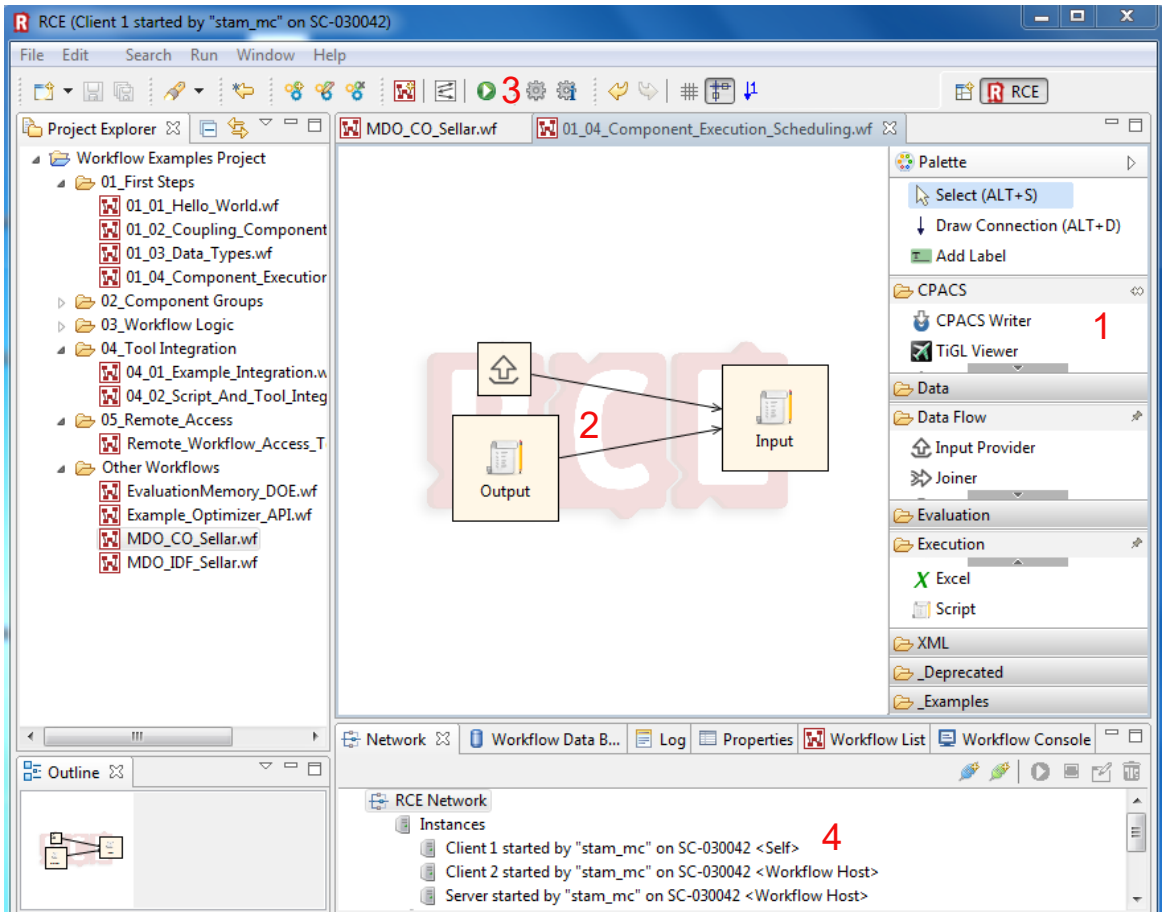

Figure 10: RCE instance

standard components called Parametric Study, Optimizer, Input Provider and Output Provider. These components are necessary for effective problem solving of many research questions. Components can specify various inputs and outputs. Those are necessary to exchange data between components.

Engineers can integrate their own tools as a workflow component in RCE. These tools are called Integrated Tools and can be connected together with the standard components to contribute to a solution. Additionally, tools can be platform specific which is supported by the platform independence of RCE. Due to the distributed environment, components can be published within a project environment for collaboration purposes. It is extremely important for integrated tools which may offer unique features. All workflow components available in the project environment are contained in the palette marked with 1 in Figure 10. Components can be simply dragged from the palette and dropped into the so-called Workflow marked with number 2.

Extension features of RCE are offered through the integration of own tools. In addition, users can develop new features in form of Python scripts. Those scripts can be executed in the standard Script component to contribute to the final result. The execution of scripts is performed either with Python or Jython. To interact with other components, it can process input and output values. Workflow components are an essential part of a Workflow.

Workflow Engine

A Workflow is the basis for the simulation of complex systems. A workflow describes the connection of workflow components for collaborative analysis or calculations. Users can create workflows, based on their knowledge, using local, integrated or published tools to solve a current research problem. Furthermore, they can share their know-how by integrating own tools and offer them in the distributed environment. The Workflow engine of RCE supports the tool integration and monitors workflows. During the execution of a workflow, the actual tool calculation remains at the published RCE instance. Therefore, a workflow containing local and remote components only exchanges data between the components.

Workflow components can be connected together to create a workflow in the Workflow Editor provided by RCE. The editor is located in the middle of figure 10. It show a sample workflow with three components marked with number 2. The connection between components is represented by an arrow. Additionally, it shows the data flow direction. A workflow can be executed by pushing the green arrow indicated with number 3 in Figure 10. A configuration dialog is prompted for the user. The user can individually select the RCE instances to manage the workflow and to run the calculation of each component contained in the workflow. Figure 11 shows the configuration dialog.

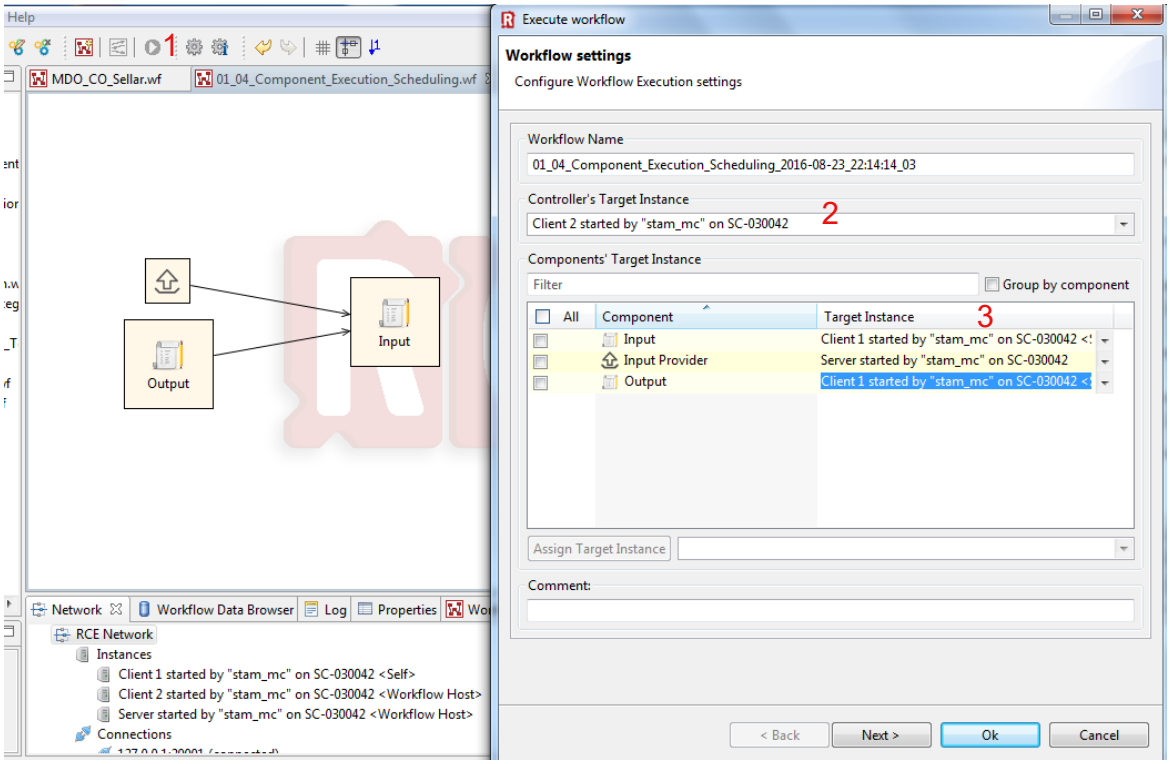

Figure 11: Example workflow execution

Data Management

The execution of research tasks usually generate a great amount of data. All participants in the research provide their data in the distributed environment. The availability and consistency of all research data is an important factor to ensure correct and plausible results. RCE produces various types of data such as simulation results of an optimization or a new airplane design. The data management component provides the storage and retrieval of data. The user interface of RCE provides the user with access to the generated data.

The data management follows a decentralized approach and thus, each instance has its local data store. The data store is accessible from any instance within the project environment. During the examination of contributed data, the user accesses the decentralized data management as a whole rather than navigating through several data stores. All workflow components store accumulated data to the data management.

Distribution

To support the distributed environment feature, RCE can be configured both as a client and server instance. Multiple instances can be connected within a network to create a common project environment. A user can use the client instance for creating workflows or to integrate self-developed tools. A server instance has two different deployment scenarios known as Tool-Server and Compute-Nodes. A tool server offers workflow components, specially integrated tools, inside the network. In particular time-consuming or computational-expensive workflows or components can be executed on a compute node. Hence, the client instance is available for further tasks.

A RCE network can be deployed without necessary adjustments to the RCE system. However, RCE can be configured to met specific network requirements. Figure 10 shows the Network View marked with number 4. New connections to RCE instances, which are within the network, can be added in the network view. Additionally, it displays the current connections of the instance. The example project environment of Figure 10 contains three instances and one of those is the local instance. RCE can be executed with and without the GUI. Usually, a server instance is started without the GUI and can be controlled via command console.

Instances can publish any workflow components, thus including the integrated tools and standard components. In addition, a RCE instance can make itself available for other instances as a Workflow Host. The workflow host is responsible for the execution of the workflows. The workflow can either be managed by the local or a selected remote instance. A remote workflow host has a further advantage. The client instance is unoccupied of the workflow execution, thus it can be turned off or be used for other activities. During the execution, the current progress can be looked up by connecting to the remote instance. All accumulated data are available during and after the execution in the data management.

In the example project environment, the two other instances are providing themselves as workflow hosts. At each workflow start, the target host can be selected as marked with 2 in Figure 11. Number 3 highlights the possible selection of instances which provide the workflow component contained in the workflow. In the example, the component Input Provider is contributed by a remote instance [SFL+12].

3.2 Application area of RCE

Initially, RCE was implemented for the shipyard industry. The reusable component-based approach of RCE makes it possible to use it for different areas. Two of those areas are space- and aircraft and for each area a real world example is described.

The first real world example is called Virtual Satellite and is an application for the spacecraft industry. It is intended to support the national satellite program. It started as an Eclipse RCP application and RCE was later integrated. The main purpose of the application is to design satellites [SFL+12].

Chameleon is a specific environment for exploratory aircraft design. The project objectives were to simulate new aircraft designs in a collaborative environment with various experts. As a result, it needed a distributed design environment and was implemented on top of RCE reusing its software components. TIGLViewer was integrated for visualizing the aircraft geometry. Chameleon focuses on aeronautic specific components build on **C**ommon **P**arametric **A**ircraft **C**onfiguration **S**cheme (CPACS). CPACS is a special XML data format designed for the exchange of input and output data between components [SFL+12].

3.3 Relevance of isolation techniques for RCE

The RCE framework is composed of a component-based and extensible software architecture. A disadvantage for those architectures are security risks involving the execution of remote code. The implementation of an appropriate security management should consider the following factors: managing permissions by establishing a security policy, establishing identities, enforcing access controls and managing user privileges [HPMS11].

The JVM provides RCE with full access to the system resources. Therefore, the whole framework including workflow components have unrestricted access. Several reasons arise to consider isolation techniques for RCE. Firstly, RCE uses a component-based approach. The workflow components might harm the underlying system. For example, the Output Provider could store large amount of data files in unauthorized directories. It can result in filling up all storage space of the system which may abruptly interrupt other workflow executions. The Script component is another possible way to harm the system. Programmed python scripts might either contain programming errors or being intentionally malicious. Due to the full access provided to the script component, the script may damage the system.

The distributed approach is another reason for considering isolation techniques to protect the host system. Publishing workflow components is a security risk, because the actual calculation stays at the published instance. For this reason, it is currently advised against publishing the script component. Integrated tools can basically contain malicious code, but the effect is limited to the published instance. Under the circumstances shown above, workflow components and especially developed python scripts can be classified as remote code. Consequently, the consideration of an isolation technique preventing possible damage by components is appropriate.

The isolation technique should be incorporated into RCE to ensure the maintainability and to guarantee the isolation is active. The access permissions of RCE should be limited and only the most necessary permissions should be allowed. Additionally, the technique should be extensible for future requirements. RCE is programmed with Java which ships with a build-in sandbox model. Hence, sandboxing should be considered for increasing the overall security of the RCE framework by restricting access to resources. The sandbox prototype should consider to implement security policies and to perform access controls.

4 Development of a sandbox prototype for RCE

The objective of this thesis is the design and implementation of a sandbox prototype for securing RCE. Firstly, this chapter describes the requirement analysis starting with the stakeholder analysis followed by the raised user stories. The sandbox model illustration of Java and OSGi are necessary for the prototype implementation. Hereafter, the elements requesting access to system resources are identified. The classification of the sandbox prototype for RCE is based on the specifications of the sandbox model of Java or rather OSGi. Subsequently, the design and implementation is described which puts everything named above together to succeed the objective. Finally, the framework architecture is explained with the new security layer and possible future extensions.

The following `font` is used for the names of Java `classes`, `interfaces`, `methods` and `keywords` within the following section.

4.1 Requirements analysis

The stakeholder and requirements for the sandbox prototype are determined for the ongoing implementation. The stakeholder analysis is performed to identify roles which are affected by the prototype. The three roles Developer, User and Administrator are determined and illustrated in Table 3.

Stakeholder	Role
Developer	specifies the maximum permissions of a bundle
User	uses a RCE instance for designing and executing workflows
Administrator	manages permissions of a RCE instance

Table 3: Stakeholder

Developers enhance existing features and implement new requirements. They are responsible for the bundles comprising all features of RCE. The user role represents scientists and engineers who are using RCE to solve research questions. The user is capable of designing and executing local and remote workflows. In addition, users can integrate self programmed tools and publish those in the project environment. Sandbox prototype introduces an administrator as a new role to manage the permissions for a RCE instance. Users are only assigned the administrator role for its own instance. During a remote workflow execution the user is not obligated to make permission decisions. Hence, a administrator is responsible for permission management of the remote instance. Division of responsibilities between user and administrator role ensures appropriate management of permissions.

The user benefits from the sandbox prototype. The prototype is implemented in order to reduce the vulnerability of the system. The developer has to contribute to achieve the objective of securing RCE. In particular, the developer is responsible to assign the appropriate permissions to a bundle of RCE. As a result, the developer should obtain professional knowledge about the permission concept of the Java sandbox model. The prototype has less influence on the user. Only the execution of a workflow can be affected. In other words, the user is not faced with permission decisions during workflow execution. Accordingly, denied permissions result in a failed workflow execution.

The sandbox prototype should provide two options to grant or deny a permission to the administrator. A permission control dialog should enable to make configurations of permissions for a RCE instance. Moreover, a dialog should be displayed for undefined permissions during the runtime of a workflow. The administrator can make temporary or permanent decisions about granting or denying the prompted permission. At any time, the administrator should be able to revoke or allow permissions by using the permission control dialog. Thus, the administrator need to gain knowledge likewise the developer about the permission concept.

All requirements of the sandbox prototype are described as user story in the product backlog represented in Table 4. User stories in the product backlog are structured in categories of similar properties. The product backlog includes the categories Instruction, RCE start configuration, Data acquisition, Configuration, Workflow execution, Persistent permission and Spike stories. Instruction category describes a user story to create a developer instruction (I1). This instruction describes how to specify a maximum set of permissions for bundles.

ID	User Story
Instruction	
I1	Developer follows an instruction about specifying maximum bundle permissions
RCE start configuration	
R1	RCE starts with active security mechanism
R2	RCE grants default permissions
Data acquisition	
D1	RCE loads all bundle names of workflow components
D2	RCE loads granted permissions for a workflow component
Configuration	
C1	RCE provides a dialog for configuring permissions for workflow components
C2	Administrator grants permissions for a workflow component
C3	Administrator edits granted permissions of a workflow component
C4	Administrator revokes permissions for a workflow component
Workflow execution	
W1	RCE shows a dialog for undetermined permissions
W2	Administrator makes a temporary decision for an undetermined permission
W3	Administrator makes permanent decision for an undetermined permission
Persistent permissions	
P1	RCE saves granted permissions persistently
P2	RCE loads persistent permissions
Spike stories	
S1	Research and describe Java Sandbox Model
S2	Research and describe OSGi Sandbox Model
S3	Research about OSGi Service

Table 4: Product Backlog

All user stories relevant at the start of RCE are included in RCE start configuration. User story (R1) is responsible to ensure that RCE is starting with active security mechanism. Additionally, the sandbox prototype should be initialized with basic permissions (R2).

Functionalities described in the Data acquisition category provide essential data for managing permissions through the configuration dialog (D1-D2). The sandbox prototype should realize a dialog for the management of permissions by the administrator (C1). An administrator should be able to allow and deny permissions for each workflow component (C2-C4). The dialog should be accessible at any time during the runtime of RCE.

During a workflow execution, undetermined permissions may be requested by a workflow component. The category Workflow execution includes user stories which provide feedback to the administrator. An approval and disapproval dialog is shown with the workflow component name and the requested permission (W1). The administrator should be able to make temporary or permanent decisions about allowing or denying the permission (W2-W3). Temporary means that the components gains the permission only for one access. Hence, the dialog may appear several times. On the other hand, the permanent decision prevents the dialog to reappear. A permanent allowed decision should be accessible and changeable through configuration dialog described above.

Granted permissions by the administrator should be stored persistently (P1) and loaded (P2) at RCE start. The prototype can work without these features. However, a restart resets all granted permissions.

The product backlog also includes Spike stories (S1-S3). Spike stories are intended to acquire essential technical knowledge. The prototype implementation requires knowledge about the Java and OSGi sandbox model (S1-S2). Both sandbox models are described in the following section. Knowledge about OSGi services is helpful for using existing services such as the CPAS (S3). Additionally, it can be useful for providing an own service to manage the permissions in RCE.

ID of User Story / Precondition	**I 1**	**R 1**	**R 2**	**D 1**	**D 2**	**C 1**	**C 2**	**C 3**	**W 1**	**W 2**	**W 3**	**P 1**	**P 2**	**S 1**	**S 2**	**S 3**
I1														X	X	
R1														X	X	
R2		X												X	X	
D1		X														
D2		X		X										X	X	
C1		X		X	X									X	X	X
C2		X				X								X	X	X
C3		X				X								X	X	X
C4		X				X								X	X	X
W1		X	X											X	X	
W2		X							X					X	X	
W3		X							X					X	X	
P1		X													X	
P2		X													X	
S1																
S2														X		
S3																

Table 5: Traceability matrix

The Traceability matrix in Table 5 shows the dependencies between the user stories from the product backlog. The rows represent the user stories and the columns contain user stories classified as preconditions. The user stories are put in relation to identify required preconditions. A dependency between a user story and a precondition is visualized by an X. A user story with

preconditions can only be implemented when all preconditions are fulfilled. The processing order of the requirements is determined based on the user stories priority and dependencies.

In addition to the requirements described in the product backlog, the following requirements need to be considered during the implementation of the prototype. Firstly, the prototype should meet the quality requirements including security improvements while providing good user experience. The general purpose of the sandbox prototype is to improve the overall security of RCE. To maintain a good user experience, the prototype should prefer to ask for missing permission rather than terminating a running workflow. Following technical requirements are necessary regarding design and implementation of the prototype. RCE is implemented in Java. Therefore, the prototype should be developed with Java. Table 6 contains technical key data relevant for the prototype development. **J**ava **D**evelopment **K**it (JDK) 1.7 is used for the development. However, RCE is executable on Java above 1.7 including the latest version 1.8. In addition, separate bundles should be created for structuring the source code. Furthermore, the prototype should be implemented without modifying existing bundles. Modification of existing code is only allowed for activating and initializing of the sandbox prototype. Finally, RCE is open source and thus, the prototype source code must comply the **E**clipse **P**ublic **L**icense (EPL).

RCE	Version 7.1.0
RCP	Version 3.7.2
OSGi	Version 4.3
Java	JDK 1.7

Table 6: Technical key data of the RCE framework

4.1.1 Usability of security

The user and particularly the usability have influence on the security of software applications. Developers should include the user as part of the security chain [WT98]. The terms Usability and User Experience are becoming more important for developers to consider in the design of secure applications. Usability refers to the user-friendliness and intuitive use of a product. For a software application, a well thought-out user interface is important for a great usability. The appearance of a product is not the focus of the user experience, but rather the interaction between user and a product [ISO06, ISO10]. In the following section, both terms are described regarding software applications.

Usability and user experience

Usability is a quality feature of a product. An easily and intuitively usable product has a well designed usability. The usability of a software application depends on the context of use. Especially for different interaction options with the application such as mouse, keyboard, touch or even movement. Usability is defined as a result of effectiveness, efficiency and satisfaction [ISO06].

The term user experience appears often in connection with usability. It describes all aspects of the experience of a user interacting with a system. The term is defined for software application in the norm EN ISO 9241-210 as follows: The awareness and reaction of a user as a result of the expected use of a product. In addition, the norm differentiates the terms user experience and usability. Accordingly, user experience includes all effects to the user which a product already has before and after the usage. On the other hand, usability has the focus on the actual

usage [ISO10]. Usability of security is explained based on a study about the usability of the Java policy tool.

4.1.2 Usability of the Java policy tool

The access control of Java is defined by external policy files containing specified permissions. Those files setup by the user or administrator. Accordingly, Java provides a graphical policy tool for creating and managing those policy files. The security policy creation is complicated and error-prone and thus security-critical. The study [HS06] shows that managing the policy files with the policy tool is inefficient and difficult for users. As a result, the users had problems with the graphical user interface of the policy tool. Furthermore, user generated policy files showed different content [HS06].

In other words, the security of applications can be enhanced by focusing more strongly on the usability. The study [WT98] proposes suggestions for solving problems with the usability to improve the security. A high priority for the security is a good designed user interface. The user should be guided through an application to learn and understand all security aspects. Security checks should be designed discreet. The creation and managing process of security policies should be intuitive for the user. The application should provide good feedback to the user avoiding dangerous errors produced by a user [WT98].

To summarize, the following usability keywords of the ISO standard 9241-11 are used to connect the problems of the policy tool with the proposed suggestions for usability: Effectiveness, Efficiency and User satisfaction [ISO98]. Firstly, Effectiveness means active support for the user during the use of an application. The support can be implemented by providing wizards to guide the user. These complies with the guidance suggestion of the study [WT98]. A wizard can be useful for the Java policy tool to train and guide novice users through the creation process. However, the Java policy tool might be helpful for users with advanced knowledge about Java security mechanisms.

Secondly, the achievement of a task measured by the use of resources such as a computer and a user is described by efficiency. Efficiency can be distinguished by the user knowledge. A novice user accomplishes a task more efficient with provided guidance and help functions. On the other hand, the efficiency of an advanced user can be increased by keyboard shortcuts to navigate through the GUI. The user fails to operate the Java policy tool. The policy file creation requires a lot of effort to figure out the necessary steps. Nevertheless, the policy tool does not provide any help functionalities.

Finally, the user satisfaction describes the acceptance of an application by the users. The acceptance can be improved by a good designed user interface. In addition, a rewarding or fun experience during the interaction with an application promotes the acceptance. The Java policy tool could increase the acceptance by being integrated into the Java runtime. For the purpose of collecting necessary permissions and the user reacts to allow or deny a permission.

In conclusion, usability and user experience are important aspects to be considered for the sandbox in RCE. The sandbox prototype should involve the administrator for securing the RCE system.

4.2 Overview of the Java Security model

The sandbox prototype for RCE is supposed to work seamlessly with the underlying framework. In this case, Java introduced a sandbox model. OSGi adds additional features to the existing Java model. Both frameworks provide APIs for accessing and extending the sandbox model to meet the needed requirements. The following subsection describes Java sandbox model (S1). It covers the evolution of the sandbox model from the first version in JDK 1.0.x to the latest version in JDK 1.2. Additionally, implementations of essential Java classes and interfaces are described and the interaction is illustrated.

The connection between the Java and OSGi sandbox model is described in subsection 4.2.2 (S2). Moreover, additional features added by OSGi are introduced such as the condition concept. OSGi provides **P**ermission **A**dmin **S**ervice (PAS) and **C**onditional **P**ermission **A**dmin **S**ervice (CPAS) for managing the application permissions. Those services are explained in more detail. The relevant Java classes and interfaces are reused in the design and implementation of the actual prototype.

4.2.1 Java Sandbox model

The Java sandbox was introduced by Java as a playground for executing external programs in JDK 1.0.x. Those programs received only limited access to available resources, the system resources. The general purpose of the sandbox is to constrain programs within its boundaries. The sandbox has the responsibility to protect certain resources of the system. Java applications have access to resources of the host system like local memory, file system, private network and the internet.

The first sandbox model was designed specially for securely executing Java Applets. A Java applet is a program executed within a web browser and it may be published on the internet from an untrusted source. Therefore, it is confined during the execution in the sandbox of Java. Since the latest sandbox model of JDK 1.2, all Java applications are able to run within a sandbox. The same security concept is used for applets and other applications. Nevertheless, applets are always executed with the sandbox. For normal Java applications the sandbox needs to be activated explicitly.

The Java class `SecurityManager` represents the Java sandbox. Java provides two approaches to enable the sandbox for an application: **V**irtual **M**achine (VM) argument or program code. Java sandbox can be activated as a standard or a custom sandbox. A custom sandbox implementation extends the `SecurityManager`. The VM argument approach is shown in Listing 1.

```
1  // default sandbox implementation
2  -Djava.security.manager
3  // or Custom sandbox implementation
4  -Djava.security.manager=CustomSecurityManager
```

Listing 1: Enable Java sandbox via VM argument

The following listing shows how to activate the sandbox via program code.

```
1  // default sandbox implementation
2  System.setSecurityManager(new SecurityManager());
3  // or Custom sandbox implementation
4  System.setSecurityManager(new CustomSecurityManager());
```

Listing 2: Enable Java sandbox via Program code

After activating the sandbox it is important to know how to manage permissions for an application. Permission management is based on a file approach for the security policy. The policy is a simple text file containing all permissions granted to the application. Listing 3 shows an example of a simple policy file including a specific file permission. Java provides the policytool for creating and editing those policy files.

```
1  grant {
2    permission java.io.FilePermission "C:\temp\readme.txt", "read,write";
3  };
```

Listing 3: Java policy file

A sandbox can be distinguished based on the restrictions established for executing a Java application. The sandbox can be classified into the following categories: Open Sandbox, Minimal Sandbox and lastly Custom Sandbox. An open sandbox provides full access to the system resources. An application receives just enough resources to be executed within the minimal sandbox not including the individual application resources. The custom sandbox provides resources to execute a Java application and further a handful of specific resources required by the application. Increasing the available resources of a sandbox model is based on trust within the application environment [Oak01]. For example, an application designed without network access may receive more access to resources in a sandbox than an application developed to access untrustworthy networks. The sandbox prototype falls into the category Custom Sandbox, because it needs to be adapted to meet the individual requirements of RCE.

Java sandbox elements

The following elements are included in the Java sandbox model of JDK 1.2 and are relevant for the development of the sandbox prototype. The core of the sandbox model is composed of `SecurityManager`, `AccessController` and `ClassLoader`.

The `System` class provides a getter and setter method to interact directly with the `SecurityManager` class. The setter method is responsible for activating the sandbox. The second method returns the actual object reference of the active `SecurityManager` which is shown in the Listing 4. The received object can be used for performing the security checks. However, the reference is `null` if the sandbox is not activated.

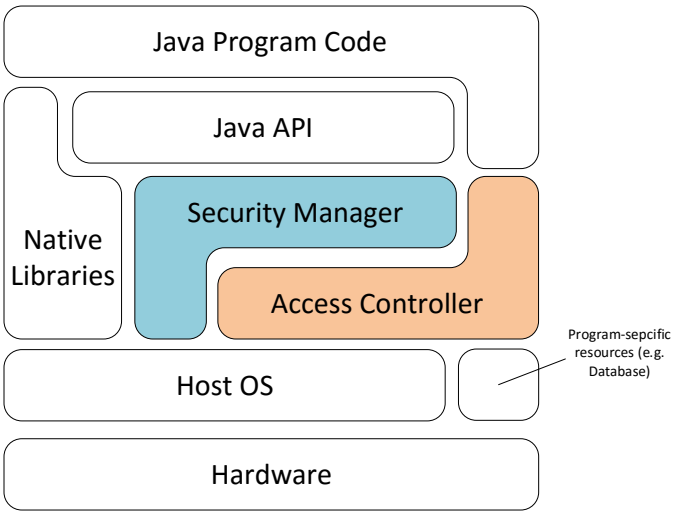

Figure 12: Java anatomy with Security Manager and Access Controller [Oak01]

The general purpose of the SecurityManager is to decide whether a security-related function should be granted access to a particular resource. The application's security policy is managed by the SecurityManager. The AccessController has the same purpose and was introduced in JDK 1.2. The SecurityManager delegates all security checks to the AccessController. Hence, the SecurityManager is supplemented with the introduction of the AccessController. Figure 12 shows the interaction of both classes.

A normal function call started in the Java program code accesses a function provided by the Java API. For security-related functions the SecurityManager is informed which delegates the call to the AccessController. It is decided based on the security policy to grant or deny the resource access. A granted call finally accesses the operating system. Whereas, a denied call produces an exception and is not forwarded to the operating system. The SecurityManager may ignore the AccessController in special cases.

Listing 4 illustrates the general approach of performing security critical methods. Firstly, a method verifies that the SecurityManager is installed. Hereafter, it can perform security calls using the security manager. The security manager throws an exception if the access is denied. Hence, the ongoing method call is interrupted by the exception. Otherwise, the method performs the actual operation [Oak01].

```
1  public int length(String fileName) {
2    SecurityManager securityManager = System.getSecurityManager();
3    if (securityManager != null) {
4      // perform security checks only if the SecurityManager is present
5      securityManager.checkRead(fileName);
6    }
7    int length;
8    // method code goes here
9    return length;
10 }
```

Listing 4: Performing security check

Permission class encapsulates an operation request to a specific resource. Permission represents the basis class and Java provides several standard permissions in the Java API. For example, Java API contains the AllPermission class to grant access to all resources and a specific permission representing the file resource which is called FilePermission. The permission type, name and actions are the key elements of a permission object.

The example policy file in Listing 3 contains a permission entry. Each permission entry in the policy file starts with "permission" and ends with a semicolon. The key elements of a permission declared after "permission" in the following order: type, name and actions. The example shows a permission for the file readme.txt with read and write access. The declaration of the name and action can be left out for the AllPermission. The permission object is used for two different purposes. Firstly, a permission can be assigned to a class which grants the class to access the resource represented by the permission. Secondly, the AccessController makes a decision based on a permission object to allow or deny the call of an operation.

The ClassLoader is responsible for loading necessary Java classes during the execution of a Java application. Additionally, it determines a set of permissions for the loaded class. A ProtectionDomain is constructed for the location of a loaded class. The protection domain contains all granted permissions for the specific location. During a security check for a particular permission the AccessController examines all active protection domains on the stack to be in possession of the permission to continue the method call [Oak01].

The above described elements of the sandbox model are illustrated in Figure 28. The figure shows the interactions between the Java classes composing the sandbox model. A summary of the Java classes and interfaces is described in Table 9.

Evolution of the Java sandbox

The first sandbox model was introduced through the JDK 1.0.x. It established an isolated environment, as represented in Figure 13, which restricts the execution of remote code. Local code has full access whereas remote code is untrusted and executed within the sandbox. The sandbox limits the access to resources of the host system. The Figure 13 shows the system resources split up into operating system and hardware.

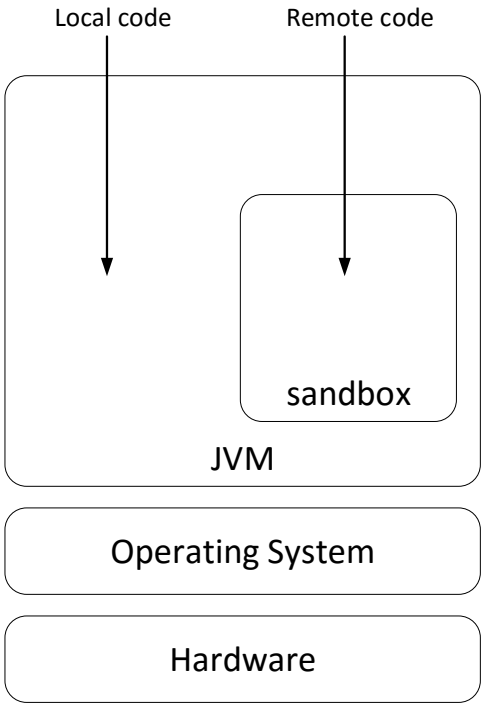

Figure 13: Security Model of JDK 1.0.x [GMPS97]

The sandbox is implemented through access control and protection of all running programs in the JVM. A `SecurityManager` class controls the access to essential system resources and limits the effect of remote code. The running programs are secured by a `ClassLoader` class enforcing a name space which allows programs to run for them self without interference with other programs [GMPS97].

First enhancement of the sandbox model was introduced in JDK 1.1 by recognizing signed remote code. A signed remote code obtains the same permissions, as local code, to access all system resources if the signature is valid.

Figure 14 represents the latest improvement of the sandbox model implemented in JDK 1.2. The access control checks local and remote code equally and grants different permissions for the execution. In order to customize the access control for an application, a developer has to activate and customize the SecurityManager and the ClassLoader. The `SecurityManager` provides several methods to perform security checks like `checkRead()`. Before the sandbox model of JDK 1.2, a new check method had to be added to the `SecurityManager` for each new access privileges. JDK 1.2 introduced the permission concept and a checkPermission() method to the `SecurityManager`. The method can be used to handle new permission checks without the need of writing new methods. In addition, security policies are easily configurable and they grant permissions for the executed code based on specified properties. Java provides a set of permissions and lets the developer create and use individual permissions [GMPS97].

Code receives different limitations depending on the execution location within the JVM. Code directly executed within the JVM has full access to all system resources. The default sandbox provides the highest limitation of access to resources. Figure 14 represents protection domains as rectangles within the JVM. The protection domains limit the access to resources in different degrees depending on the granted amount of permissions [GMPS97].

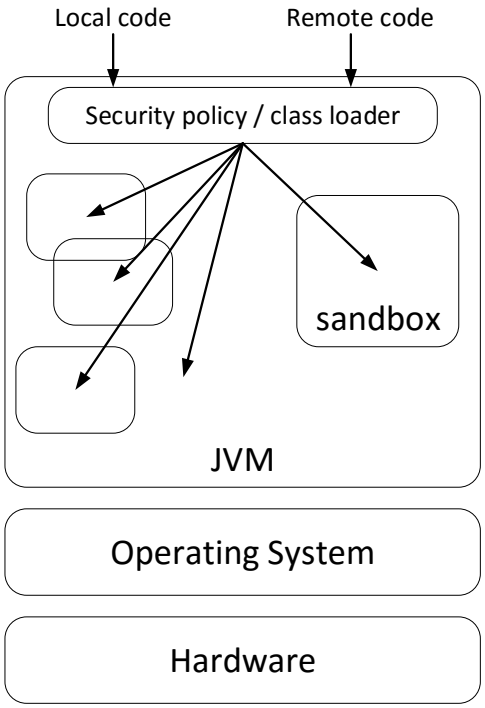

Figure 14: Enhanced Security Model of JDK 1.2 [GMPS97]

The `AccessController` decides whether a certain permission should be granted or denied based on all protection domains currently on the stack at the call of the access controller. A sample stack traces is illustrated in Figure 15. The stack trace is relevant because the access controller only checks classes and the corresponding protection domain currently on the stack. The example shows four classes on the stack which belong to three different domains. The security check was triggered by the `write()` method of the input provider. During the security check, the effective permissions are the intersection of all permissions contained in the protection domains on the stack. In other words, the particular permission must be granted to all domains to proceed normally with the triggered operation. However, if only one domain is missing the permission a security exception is thrown to interrupt the method call. For example, consider all protection domains on the stack except the input provider domain are granted to write to files. The access control fails because the file permission is not part of the effective permissions. However, the access controller provides a method to grant temporary the access to a system resource.

Java provides a privileged call which enables a class to execute an operation without controlling the actual permission. For instance, the input provider is not allowed to directly write to the file system. Whereas, the file utils class is granted write access to files. Classes who have access to the file utils class should be allowed to temporarily access a file. Therefore, `FileUtils` can use the `doPrivileged()` method to temporarily allow the file permission to all classes. To summarize, the input provider is now able to access a file, because it is temporarily granted the file permission by file utils.

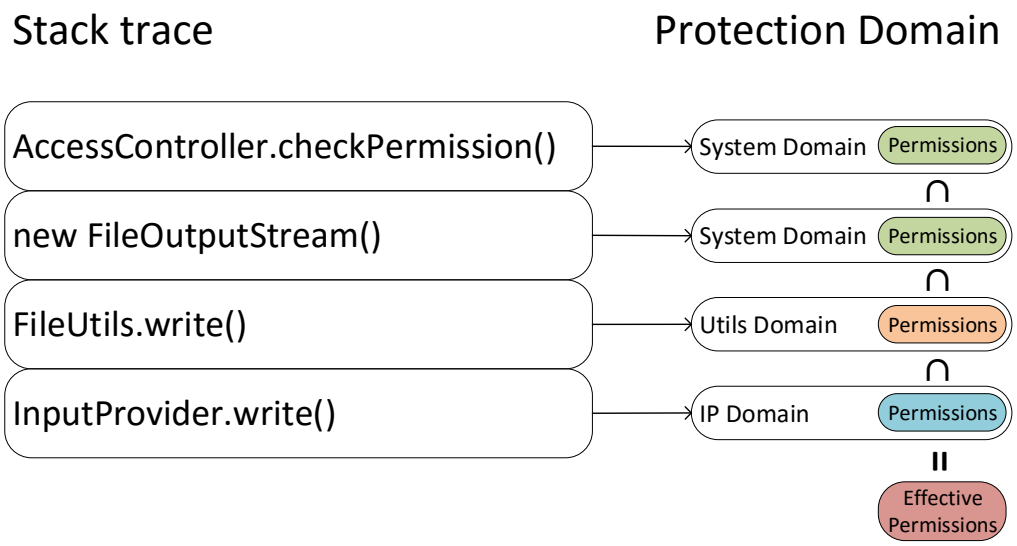

Figure 15: Stack trace during a security check [Oak01]

4.2.2 Security in Eclipse Equniox/OSGi

The Java 2 sandbox model forms the basis for the sandbox model of the OSGi framework. OSGi provides an extensible and comprehensive sandbox model to be easily adaptable for securing applications. Eclipse Equinox implements the OSGi specification and developers can take advantage of the Java and OSGi sandbox model to secure their RCP applications [HPMS11].

OSGi established the bundle concept for reusable functionalities of loose modules. The file-based approach of the Java sandbox model is unsuitable for managing security policies at bundle level. Therefore, OSGi introduced two framework services called **P**ermission **A**dmin **S**ervice (PAS) and **C**onditional **P**ermission **A**dmin **S**ervice (CPAS). Those services provide APIs for permission management at the bundle level which is more suitable for the modular and dynamic architecture. CPAS provides the management of permissions in real time. Hence, changes to the permissions are effective without application restart.

Additionally, the `Condition` approach is introduced by OSGi. Security policies define permissions to access specific resources which can be guarded by conditions. For example, a condition can be based on the bundle location, bundle signature or custom conditions. It allows to grant permissions to bundles which satisfy the conditions. The custom conditions can vary from the application context. A benefit of the condition approach is that a custom condition may present a dialog to receive an approval or decline of the user to certain permissions.

The sandbox of a RCP application is activated by installing a security manager. However, the default implementation of the security manager is insufficient. Eclipse Equinox provides a custom security manager class called `EquinoxSecurityManager`. To activate the sandbox, an Eclipse RCP application must be started with one of the following VM arguments:

```
1  // Eclipse Equinox sandbox implementation
2  -Declipse.security=osgi
3  // or
4  -Declipse.security=org.eclipse.osgi.internal.permadmin.
       EquinoxSecurityManager
```

Listing 5: Enable Eclipse sandbox

Both arguments install the `EquinoxSecurityManager`.

Eclipse Equinox/OSGi sandbox elements

The following description of relevant sandbox elements are included in the RCP version 3.7.2 which implements OSGi in version 4.3. Hence, the elements are available in the development of a sandbox prototype for RCE.

The class diagram shown in Figure 16 composes all necessary classes, interfaces and their relationship for developing the sandbox prototype. The diagram is divided into the sandbox API of OSGi (upper half) and the actual implementation of Eclipse Equinox (lower half). The OSGi API classes are used to create the design of the sandbox prototype. The diagram contains classes provided by the API of Java (orange), OSGi (blue) and Eclipse Equinox (green). Furthermore, extension options of the sandbox model are visualized by the gray classes.

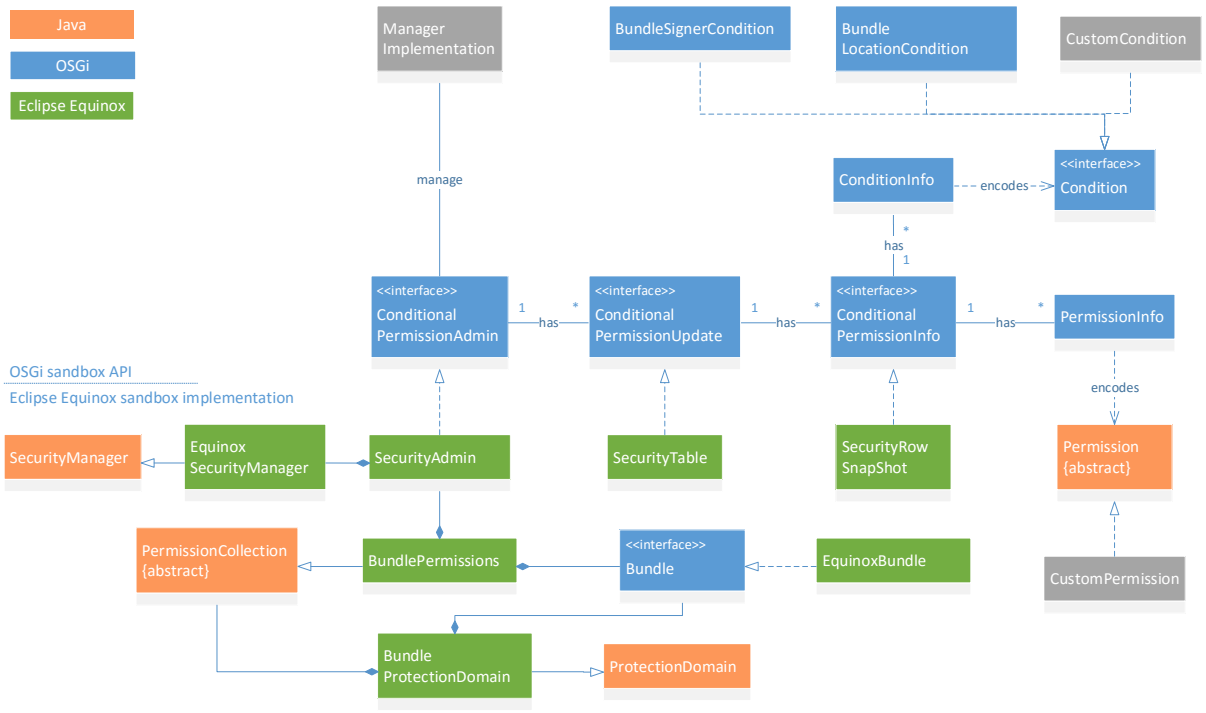

Figure 16: UML class diagram of the Eclipse Equinox/OSGi Sandbox model [OSG11]

The core element of the sandbox model is the `ConditionalPermissionAdmin` service. It is part of framework services of OSGi. The general purpose of CPAS is to support a management implementation to enforce and control a security policy of the application. Eclipse Equinox provides a concrete subclass of the services called `SecurityAdmin`. To work with the `SecurityAdmin`, the CPAS can be requested from the service registry. CPAS is initialized during the start up of framework. It is available independent of the installed security manager. However, the permission management is useless without security controls. `EquinoxSecurityManager` should be used in connection with the CPAS.

CPAS provides an API to enforce and manage the security policy which is represented as the so-called policy table. The policy table is valid for the whole system. It is composed of policy entities. The `ConditionalPermissionInfo` class describes the content of a policy. The policy keeps information about the access type, conditions, permissions and a unique name. Listing 6 shows example policy entries. The syntax of the policy entry starts with the access type and ends with the unique name. The conditions and permissions are specified inside of the curly brackets. Each condition is encoded within square brackets and each permission within round

brackets. The encoded form correspond to the classes `ConditionInfo` and `PermissionInfo`. These classes are used to construct new policies which than are added to the policy table. [OSG11]

```
1  DENY {
2    (FilePermission "C:\System\*" "read,write")
3  } "System folder"
4  ALLOW {
5    (FilePermission "<<ALL FILES>>" "read,write")
6  } "Allow File access"
7  DENY {
8    [BundleLocationCondition "file:inputprovider"]
9    [TimeCondition "before" "11:30"]
10   (PackagePermission "de.rce.security.*" "import")
11 } "Deny security package import"
12 ALLOW {
13   [BundleLocationCondition "file:inputprovider"]
14   (ServicePermission "LogService" "get")
15   (PackagePermission "*" "import")
16 } "Basic permissions"
```

Listing 6: Policy entries: File permissions

The policy file of the Java sandbox only contains permission which are than granted to the application. In OSGi, permissions can be determined to allow or deny the access to a resource. For example, Listing 6 grants permission to access all files on the system. However, there is a specific folder which should never be accessed. Therefore, the permission system folder denies the access to the particular folder using the deny access type. In this case, the order of permissions is important. During a security control, the first satisfied condition provides the permission whether the access is allowed or not. In particular for the example, the permission denying the access to the specific folder should appear first. Otherwise, the permission "Allow File access" would grant the access to all files.

A manager implementation can access a copy of the policy table using `ConditionalPermissionUpdate`. During the access of the table, the manager can iterate, add and delete policies from the table. The manage must commit the changes to make them effective for the application. The introduced protection domain in Java is extended to support the bundle concept of OSGi. A new `BundleProtectionDomain` is produced and associated for each started bundle. Each bundle is granted with a set of permissions. The permissions allow all classes within the bundle to perform certain operations with access to the resources. Therefore, the bundle protection domain accesses the policy table to collect potential permissions which are applied to the bundle. During a security check, all protection domains require the same permission to proceed with the operation as described for the Java sandbox model.

A `Condition` protects permissions and must be satisfied to grant the protected permissions. A set of permission can be guarded by several conditions as showed in Listing 6. All conditions must be met to grant the protected permissions. Furthermore, it is possible to add permissions without a conditions. As a result, all bundles are granted the permissions. The evaluation of multiple conditions can be expensive and may influence the performance of the application. Two approaches are introduced to reduce the evaluation time. Firstly, a condition can be mutable or immutable. For immutable conditions, the evaluation is proceeded only one time per bundle protection domain and the result is cached. A condition may change from mutable to immutable, but the other way around is not possible. Secondly, the evaluation of conditions can be performed immediately or postponed. Postponing the evaluation may be necessary for certain conditions such as interacting with the user.

Evolution of the OSGi sandbox

Two framework services provided by OSGi are intended to manage the security policy for an application. Up to OSGi version 4.0, **P**ermission **A**dmin **S**ervice was the standard service to maintain the security policy. It provided functionalities to receive information about current permissions of bundles. Furthermore, it allowed management agents to add permissions before, during and after the installation of a bundle. PAS provided default permissions for bundles which are missing specific permissions [OSG03]. Since OSGi version 4.0, PAS is replaced by **C**onditional **P**ermission **A**dmin **S**ervice. However, `SecurityAdmin` of Equinox implements both services. It is recommended for new implementations to use CPAS, because CPAS can do everything PAS can do and the more powerful condition concept can be used [WHKL08].

OSGi version 4.0 introduced the condition concept along with the **C**onditional **P**ermission **A**dmin **S**ervice. The service is available at the service registry. A manager implementation retrieving CPAS should directly set `AllPermission` to the management bundle. All permissions are necessary for the bundle to manage the permissions for the whole application. Afterwards, the manager can enforce a security policy by adjusting permissions for other bundles.

The bundles effective permissions are composed of the following three permission types: implied, local and system. Implied permissions are granted by the OSGi framework, because they are necessary for default operations. For example, a bundle is granted full file access to the own bundle storage area.

Moreover, own permissions so-called local permissions can be contained within a bundle. Local permissions are specified as a resource at the bundle location. The general purpose of local permissions is to determine maximum permissions necessary for the bundle. Accordingly, a bundle never receives more permissions than the local permissions, but it may receive less. These permissions are defined by the developer who can ensure that a bundle is never granted more permission than it actually requires. The OSGi framework enforces the local permissions. However, the bundle is granted with `AllPermissions` when the permission resource is not available. Additionally, local permissions support the review of required permissions before being installed in an application. The resource for local permissions has the name "permissions.perm" and must be stored in the "OSGI-INF" directory of the bundle. The content of the resource can be as followed:

```
1  # Local permissions of input provider
2  (ServicePermission "*" "import,export")
```

Listing 7: Local permissions resource

It can contain comments starting with #. All other lines describe a permission representing the encoding of `PermissionInfo`. Lastly, thesystem permissions are granted by either PAS or CPAS. The effective permissions of a bundle are always equal or less than the local permissions. Effective permissions are calculated as shown in the following formula:

$$Effective = (Local \cap System) \cup Implied$$

OSGi ensures that effective permission is equal or less than the local permissions.

The OSGi framework provides four custom permissions for protecting sensitive resources of the module, lifecylce and service layer. `PackagePermission` and `BundlePermission` belong to the module layer. The package permission is used to control the imports and exports of a bundle. A bundle may require on another bundle which must be allowed specifically by the bundle permission. The lifecycle layer contains the `AdminPermission` which protects essential lifecycle functionalities. The last permission is part of the service layer and is called `ServicesPermission`. Similar to the package permission, service permission is used to allow

a bundle to register or receive a service.

The introduced condition concept is very powerful for managing permissions. OSGi provides two default conditions to grant permission based on the bundle location and the bundle signer. Additionally, it provides a developer to create custom conditions to efficiently enforce the security policy. To eliminate all security-risks, all conditions are loaded from the framework class path. Thus, the bundle of a custom condition must be available for the system bundle: `Fragment-Host: system.bundle; extension:=framework`

Such an extension include limitations for the condition bundle, because it is not allowed to import or require other bundles. The implementation of a condition is limited to the Java and Eclipse Equinox API. For example, a user dialog can not be programmed with **S**tandard **W**idget **T**oolkit, because it requires the import of another bundle. A custom condition implements the `Condition` interface and it needs to provide the following constructor or static method:

```
1  public class CustomCondition implements Condition {
2    public CustomCondition(Bundle b, ConditionInfo i) {}
3    public static Condition getCondition(Bundle b, ConditionInfo i){
4      // return instance
5    }
6  }
```

Listing 8: Custom condition [HPMS11]

The class diagram in Figure 16 describes the static relationship between the elements composing the sandbox model. Figure 17 provides an example of the interaction of elements during an access control of a RCP application. Usually, a security check is triggered through a call to the installed security manager. In this case, the `EquinoxSecurityManager` performs a privileged call, thus triggers the internal check. The internal check passes on the permission check to the `AccessControlContext`.

During the check, the context has access to all available protection domains on the stack. In particular, the protection domains are represented by `BundleProtectionDomains`. All domains are verified in a loop that the permission is granted or can be implied from other permissions. The implied permissions provided by the framework are reviewed first within `BundlePermissions`. Eventually, `SecurityAdmin` verifies the permission against local and system permissions. Accordingly, the checked permission is either implied by the effective permissions or a security exception is thrown. In the case that the permission can be implied, the security manager continues to loop through all postponed conditions. A security exception may be caused, if only one condition can not be satisfied. Otherwise, the operation which triggered the security check is granted to access the sensitive resource.

To summarize, all essential concepts and elements of both sandbox models are described. Therefore, the spike stories (S1-S2) are successful performed and provides an excellent foundation for the design and implementation of the sandbox prototype.

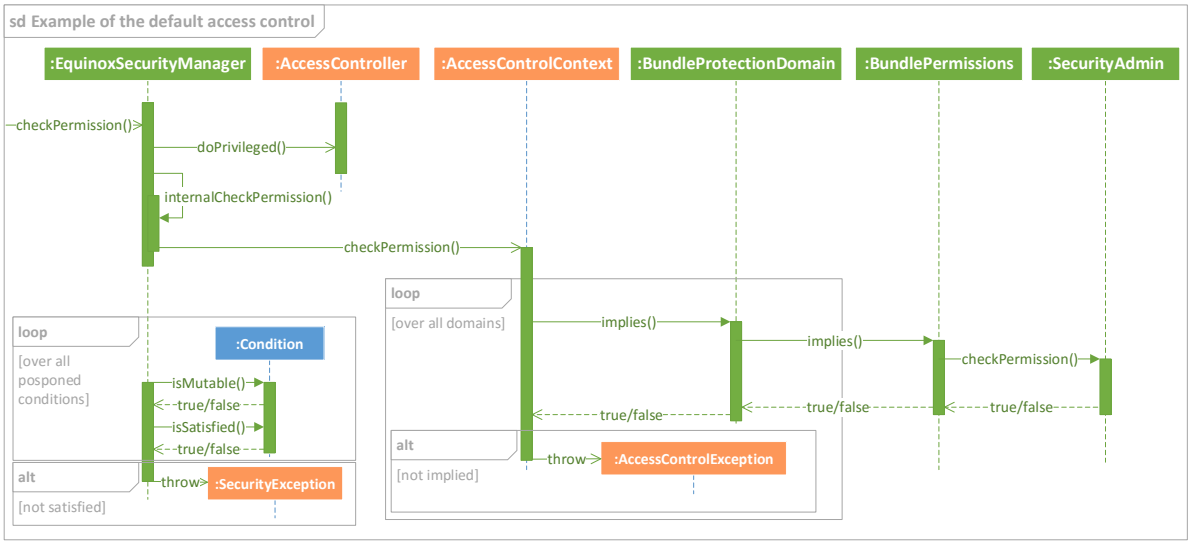

Figure 17: UML sequence diagram: example interaction during a security check

4.3 Identification of elements requesting access to system resources

The identification of elements requesting access to system resources in RCE includes collecting information about which resource is accessed by an element. An element describes a single bundle. A bundle may belong to a workflow component, the RCE framework or the Eclipse framework. Those information are essential for designing and developing the sandbox prototype. Based on the collected information, granting permissions within the sandbox can be simplified and be confined to only the necessary permissions. Additionally, elements which require the same permissions can be classified in groups. Such a group could be the workflow components.

The following relevant information must be collected which arise from the previous section about the sandbox model in of Java and OSGi: Bundle name, Permission Type, Permission Name and Permission Action. The bundle name is relevant, because permissions are granted for each bundle. Java and OSGi provide standard permissions for various system resources. Additionally, developers are able to implement custom permissions. Therefore, its significant to identify the type of a used permission. A permission of the same type can vary from the name and actions. For example, a file permission can specify different path as the name and it could either be a read or write access. Hence, the name and action are important to collect.

Permission checks are performed when RCE is started and used with the sandbox enabled. To collect the information stated above, the permission checks should be logged while executing example workflows within a common project environment. Java provides an adjustable security debugging configuration. Thus, enables to monitor the permission control. Various adjustable output options are available for the security debugging. Interesting options for the permission checks are "all" and "access". The output of option all includes all information about the control. Instead, the access option only creates output of the method `AccessController.checkPermission(...)`. In addition, access has the following three additional settings for adjusting the output: "stack" includes the entire stack trace, "domain" prints the content of all protection domains of the current context and "failure" only prints the content of stack and domain if the permission is denied [Ora].

However, Java security debugging only covers the introduced permission concept. The output is not sufficient for an Eclipse RCP application, because the bundle information is missing. Consequently, a custom logging must be implemented to meet the requirements. `BundlePermissions` and `SecurityAdmin` are identified to provide information about the bundle and permission during a security check. The custom logging is added to the `checkPermission()` method of `SecurityAdmin` shown in Figure 17. In other words, the logging only considers permission which are not granted by the implied permissions. Those permissions are granted to each bundle and the permission is always granted. For including the implied permission, the custom logging should be called at the beginning of the `implies()` method of `BundlePermissions`.

The custom logging collects the information about bundle and permission during a permission check. For the result, only bundles of RCE and Eclipse Equinox are considered. The appearance of identical permissions increase a counter. At the beginning, a permission distinguished by its typ, name and actions. However, the execution of RCE collected a large amount of different permissions. Some permissions appeared only one time. For example, the access to two different files is counted differently, because the permission name varies for both permissions. Whereby, the collection of permissions was slightly adjusted to only collect the bundle name, type of the permission and number of permission requests.

The above described custom logging is able to collect the necessary information. The following approach is documented to reproduce the logging results.

Preparations: Starting a common project environment with two clients and one server. Both clients are connected to the server. The server and client 2 are available as workflow host in the network. Furthermore, the server published the Script component which are used in the following workflow execution.

Execution:

1. Creating the Workflow Examples Project on both clients
2. Deleting the project from client 2
3. Executing the example workflow Hello World containing one Script component. The workflow is executed five times by using a different workflow host and publisher of the Script component
   a) Client 1: component and workflow host
   b) Client 1: component, Server: workflow host
   c) Server: component and workflow host
   d) Server: component, Client 2: workflow host
   e) Server: component, Client 1: workflow host
4. Executing the example workflow Simple Loop containing three Script components and one Design of experiments component creating a loop. The workflow is executed three times by using a different workflow host and publisher of the Script component
   a) Client 1: component and workflow host
   b) Client 1: three components, Server: one Script component and workflow host
   c) Client 1: two components, Server: two Script components, Client 2: workflow host
5. Accessing data management and navigating through entries on client 2

The above described approach created three log files containing the bundle and permission information.

To summarize the results, Table 7 shows all requested permissions during the lifetime of the project environment. In total, 20 different permissions are requested in RCE. The columns correspond to the number of request of a certain RCE instance. During the application lifetime

Permission Type	Client1	Client2	Server
AdaptPermission	21,753	968	6,979
AdminPermission	14,295	15,909	8,290
AllPermission	2	2	2
ApplicationAdminPermission	1	1	1
BundlePermission	1,587	1,595	1,603
CapabilityPermission	613	617	621
ConfigurationPermission	440	440	599
FilePermission	231,037	81,884	136,606
LoggingPermission	21	21	21
ManagementPermission	7	7	7
MBeanPermission	6	6	6
MBeanServerPermission	4	4	4
MBeanTrustPermission	3	3	3
PackagePermission	10,542	10,614	10674
PropertyPermission	5,068	1,945	985
ReflectPermission	1,435	923	1,227
RuntimePermission	193,740	34,597	129,288
ServicePermission	281,955	205,404	209,777
SocketPermission	27	27	65
TopicPermission	26,216	2,353	9238
Total permission requests	**788,752**	**357,320**	**515,996**

Table 7: Requested permissions

and execution of workflows, a large amount of permissions are requested. Client 1 performed the most request with over 700,000, because all workflows are started on this instance. The `FilePermission` and `ServicePermission` are requested with noticeable high amounts on all three instances. Additionally, the `SocketPermission` was requested more often on the server instance. The socket permission protects all access to create or listen to a network. The higher amount of socket requests is appropriate, because the server provides connection between other instances in the network. Therefore, Section A.3 shows differences between the instances for requesting the socket permission.

4.4 Classification of the sandbox prototype of RCE

The sandbox prototype falls into one of the three sandbox categories described in Section 2.2. The classification is based on the properties of the sandbox implementation in Java and OSGi. Key properties of both sandbox models is illustrated in Figure 18. Java introduced a mechanism for controlling the access to sensitive resources with the `SecurityManager` class. Sensitive resources are represented by certain `Permissions`. For example, `FilePermission` represents the access to the file system. OSGi build the sandbox model on top of the established API of Java. Therefore, the permission concept is carried on to enforce a security policy for an application. Furthermore, the condition concept was introduced by OSGi. The purpose of `Conditions` are to guard a set of permissions. First, the conditions must be satisfied to be granted the guarded permissions and thus to gain access to the system resource.

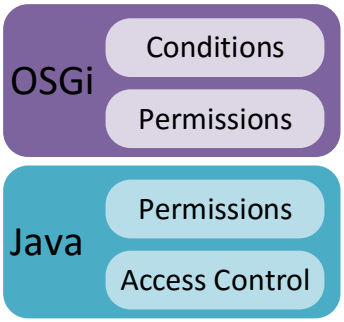

Figure 18: Sandbox properties of Java and OSGi

The sandbox prototype for RCE enforces a security policy by performing conditional permission management. Hence, access control, permission and condition concept must be considered for classifying the sandbox prototype. Table 8 describes the correspondence of the three sandbox approaches with the above identified properties. A match between a property and a sandbox approach is visualized by an X.

Property / Sandbox approach	**ISA**	**ABI**	**ACL**
Access Control		X	X
Permission			X
Conditions			

Table 8: Sandbox prototype classification

Instruction **S**et **A**rchitecture (ISA) constrains all activities performed by tasks between the operating system and the hardware. The execution environment of Java applications are located on top of the operating system. ISA is located on a completely different computer layer. Hence, it matches non of the properties.

Application **B**inary **I**nterface (ABI) prevents certain calls to be forwarded to the operating system determined by configuration files. The restriction matches the access control property. Additionally, those configuration files serve a similar purpose compared to the policy files used for the Java sandbox. However, the permission and condition approach is not supported.

Access **C**ontrol **L**ist (ACL) controls the access to system resources by providing a set of permissions. Those permissions apply to potential security-sensitive resources such as file system and network. Therefore, ACL matches with two properties as shown in the Table 8. The advanced condition approach is hereby not supported. However, the access control performs based on the permissions. The condition concept establishes an additional security layer which decide to grant or deny a permission.

In summary, the sandbox prototype falls into the ACL sandbox category which complies the most identified properties.

4.5 Design and implementation of the sandbox prototype for RCE

The user stories described in the product backlog 4 are required for the success of the prototype implementation. The spike stories (S1-S2) are previously described. The gained knowledge is used in the design and implementation. The section is divided into design and implementation activities.

The design section develops a concept in virtue of the user stories. Firstly, the relationship between functional user stories is illustrated by an use case diagram. The concept suggests dialog prototypes for the interaction between the administrator and the RCE system. Permission groups are identified based on the logging results. Lastly, the extension options illustrated in the class diagram 16 are considered for the implementation.

The execution of the concept is described in the implementation section. It includes the implementation of the prototype dialogs. Moreover, the approach is explained how write access to the data management is granted and which alternative exist. Finally, a class diagram illustrates all relevant classes of the implemented prototype.

4.5.1 Design

The developer instruction (I1) is described in Section A.2. All developers are advised to gain knowledge about the permission concept and to identify the maximum amount of permission used by their bundle. Specifying the maximum set of permissions has several benefits. First of all, a bundle can never receive more permissions than required. Developer must ensure that the bundle works properly with the determined permissions. Other developers can quickly review required permissions and identify potential security-risks. RCE is designed to offer extension features. Bundles created by third party developers can be easily reviewed in terms of local permissions. Accordingly, local permissions are excellent for decision making whether the bundle should be integrated into RCE.

The RCE launch configuration must be edit for the purpose of activating the security mechanisms in RCE (R1). One of the VM arguments shown in Listing 5 must be added to the launch configuration. During application start, the following code ensures that RCE only starts with active sandbox:

```
1  if(System.getSecurityManager() == null) {
2    throw new IllegalStateException("Install a security manager to start
         RCE.");
3  }
```

Listing 9: Start RCE only with active sandbox

At start up time, the management of permission should be initialized by providing default permissions (R2). The logging results of bundles requesting permissiosn in RCE is used to identify permission groups. The following three permission groups can be identified: framework, workflow components and standard. The permission granted vary from the permission group.

First group, the framework group receives `AllPermissions` based on specific bundle locations. Hence, the permission is guarded by the `BundleLocationCondition`. The purpose is to ensure that Eclipse Equinox and the RCE framework bundles can perform all necessary operations without restrictions. Therefore, all bundles belonging to the Eclipse and RCE framework compose the framework permission group. The bundles can be identified by the prefix of "de.rcenvironment.core", "de.rcenvironment.platform" and "org.eclipse". Each bundle must be granted with the permission separately, because the bundle can always satisfy only one location

condition. For performance reasons, the bundle responsible for the permission management should be added to the permission table as first entry. All changes to the permission table requires all permission and triggers a security check. The security check completes faster when the first entry grants the permission to the manager bundle. The bundle and classes for managing permissions is created in the process of the prototype.

The second permission group are all bundles composing workflow components. All workflow component bundles have the same prefix "de.rcenvironment.components". The workflow component permission groups is granted with `ServicePermission` for publishing and requesting services. There are currently 84 workflow component bundles available and 29 of those already request services provide in RCE. Additionally, new bundles and extensions should have the opportunity to publish and request services. Granting the service permission complies with the requirements of the reusable approach of RCE. Each component bundle is granted the services permission protected by a `BundleLocationCondition`.

Standard is the last permission group. Its purpose is to grant standard permissions to all bundles. The following three permissions are requested by the majority of all bundles: `PackagePermission`, `BundlePermission` and `CapabilityPermission`. Those three permissions should be granted without a condition. As a result, each bundle protection domain is granted those permissions.

All functional user stories are illustrated in the use case diagram shown in Figure 19. Additionally, the relationship between the user and administrator role is visualized. A user has automatically the administrator role for the own local instance. During the execution of workflows, the user is not granted the administrator role on remote instances. A use case is described as an ellipse within the boarder of the RCE system.

All grey use cases are already implemented in the RCE framework. They are included to show the purpose of the user role and how the security check is triggered. The use case security check has a grey orange color indicating that it is available, but it must be activated. The use case is activated through installing a security manager in RCE (R1). The blue use cases are subject to be implemented for the sandbox prototype.

A user can only execute a worfklow at a local or remote RCE instance. The execution triggers the security check for accesses to sensitive resources. Four functionalities are available for the administrator the whole time. However, one functionality can only be used when triggered by the security check.

OSGi sandbox model is the foundation of the sandbox prototype. Three extension options are provided as illustrated in Figure 16. A manager implementation is necessary to manage the security policy. Permissions may be protected by a custom condition. Lastly, custom permissions can protect sensitive resources within the RCE framework. The extensions provided by the OSGi sandbox model are mapped to the user stories of the prototype.

Manager implementation

OSGi provides the **C**onditional **P**ermission **A**dmin **S**ervice (CPAS) to manage permissions at the bundle level. A manager class should be implemented for the prototype to offer functionalities to manage RCEs permissions. The manager class is required by the following user stories: R2, D1-D2 and C1-C4.

First of all, the default permissions must be initialized (R2). The above specified permission groups receive certain permissions which must be added to the policy table. Therefore, the manager class must provide an initial operation.

The administrator can interact with the manager class through a dialog provided by the use

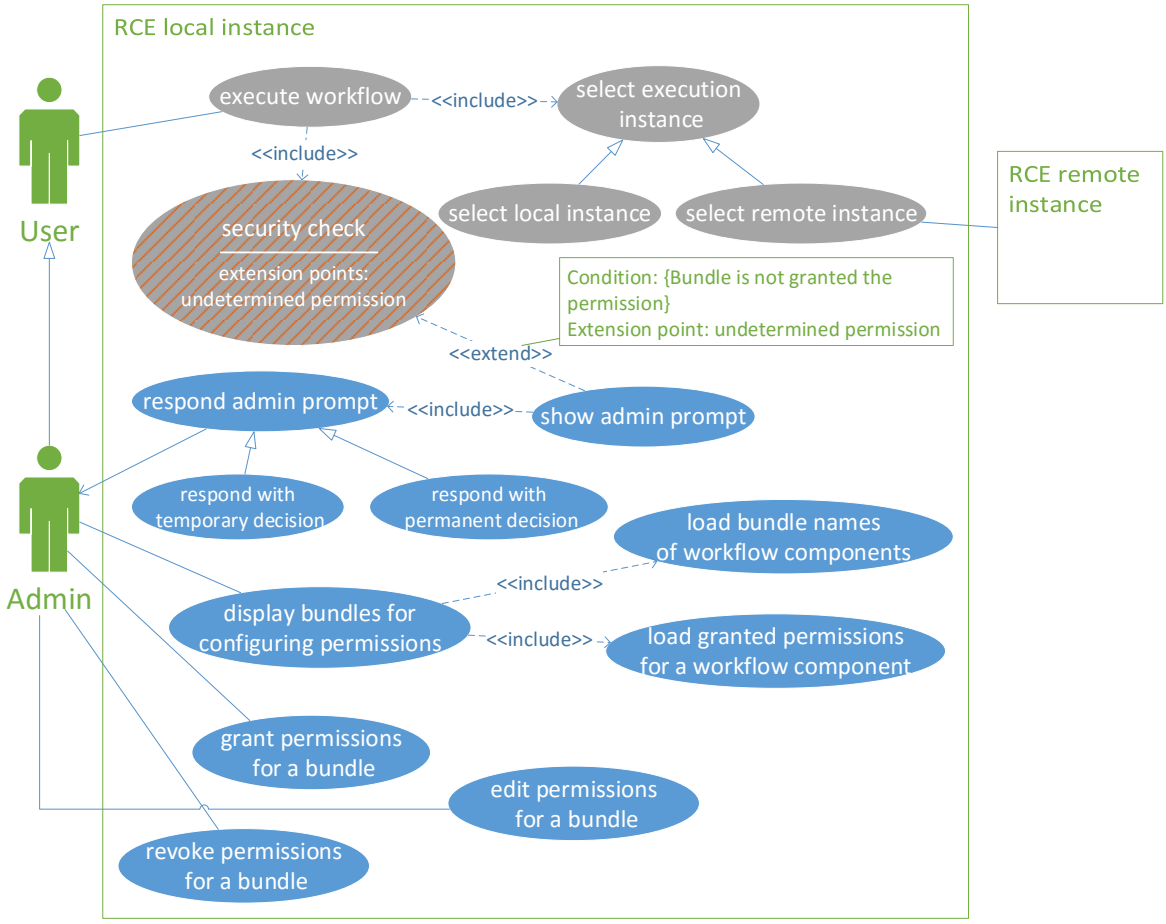

Figure 19: Concept UML Use Case diagram

case display bundles for configuring permissions (C1). The use case includes the two use cases of the data acquisition category. Both are used to load relevant information to be displayed in the dialog. First, the dialog is provided with a list of all bundle names by the use case load bundle names of workflow components (D1). The administrator can select a bundle name to load and display the granted permissions of the bundle (D2). Additionally, the dialog provides the administrator to add, edit and remove permissions for a selected bundle (C2-C4).

A prototype for the permission control dialog is illustrated in Figure 20. However, it shows two different dialogs. The dialog in the background is the main dialog to display the bundles and granted permissions (C1). For adding or editing permissions, a second dialog is prompted (C2-C3). The administrator enters the permission type, name and actions. After adding or editing a permission, the dialog calls an operation of the manager class which executes the change in the policy table. To edit or remove a granted permission, the permission must be selected to enable the corresponding action buttons.

The traceability matrix 5 shows a precondition for all configuration user stories to the OSGi Service spike story (S3). The permission control dialog requires access to the manager class. Furthermore, RCE can be executed without GUI and the manager should be accessible through a command console. Hence, the manager implementation should be designed as a service and published in RCE.

The sandbox prototype works without the implementation of the user stories (P1-P2). However,

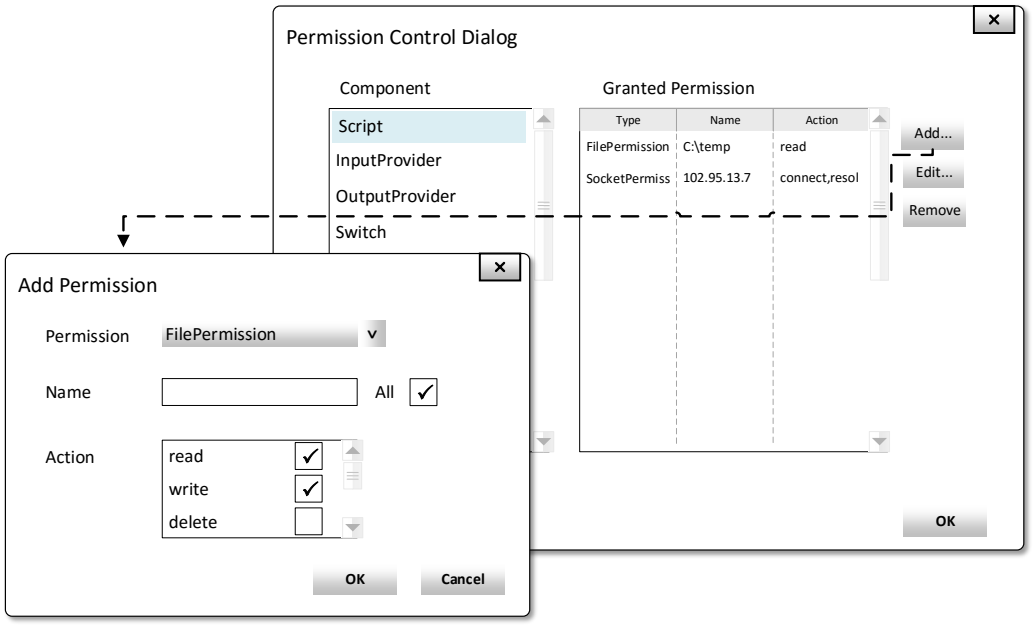

Figure 20: Permission control dialog prototype

all permissions granted by the administrator are gone after a restart of the RCE instance. All changes made by the administrator to the policy table should be persistently stored (P1). At the start up of RCE, the stored permissions should be loaded (P2). Additionally, those need to be added back to the policy table. The granted permissions should be added during the initialization of the permission groups (R2).

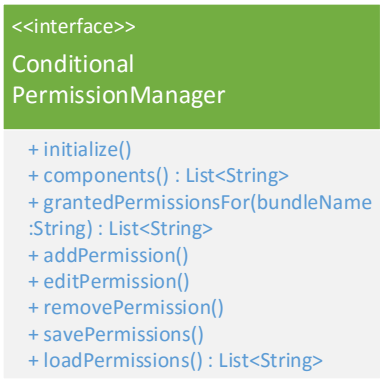

Figure 21: UML Class diagram: Manager implementation

Figure 21 shows a class diagram of the manager class providing functionalities based on the user stories described above. The class is actually an interface, due to the requirements for an OSGi service. The service must be published and the dialog implementation can request the service and use the provided operations.

Custom condition

Consider the following scenario, a workflow component is not granted a specific permission during the workflow execution. The prototype should prefer to ask the administrator to grant the permission rather than to terminate the workflow. RCE needs to provide a dialog for undetermined permissions (W1). A custom condition is a great way to interact with the administrator as identified by the spike story (S2). A new `UserPromptCondition` is to be implemented to prompt a dialog and whether or not to grant the permission. For the interaction, the user prompt condition must be a postponed condition. The proposed implementation requires the RCE instance to run with the GUI. Future improvements should considered a possible interaction with the administrator when the RCE instance is started without a GUI.

The administrator is able to make temporary or permanent decisions about granting or denying the permission (W2-W3). Hence, the condition is by default mutable. The condition may change to immutable when the administrator makes a permanent decision. In this case, the result should be cached and the dialog should not be prompted again for the bundle requesting the permission. The permission should be added to the policy table when allowed permanently (W3). For the temporary decision, the permission is only allowed for one access to the resource (W2). Therefore, the dialog may be prompted multiple times for the same resource.

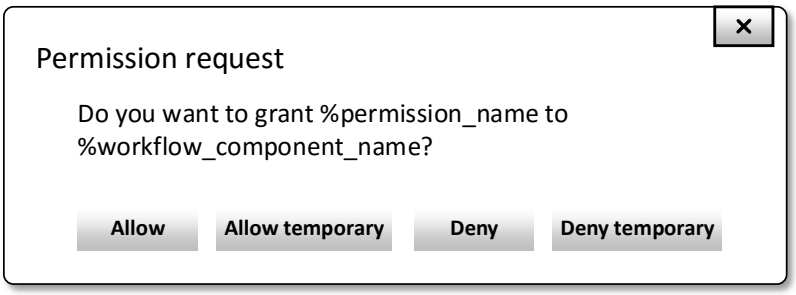

Figure 22: User prompt dialog (W1)

Figure 22 shows a prototype of the user prompt dialog. The buttons "Allow" and "Deny" are used for permanent decisions about the permission. The placeholder in the question should be replaced by the actual bundle name and permission type.

During a workflow execution, workflow components require permissions to system resources such as the file system or network. Those permissions must be added with the user prompt condition to the policy table during the initialization of the default permissions (R2). For example, undetermined access to files or network resources should prompt the dialog.

Custom permission

Custom permissions can be used to protect resources of RCE. For example, the data management is such a sensitive resource. The results of workflows can be accessed by every user of a project environment. In other words, every user can read and delete data on remote instances. In this case, a custom data management permission could protect the access to the generated data. Every user may be granted read access. However, only the instance owner is granted the delete permission. Thus, prevents users from deleting relevant research data on a remote instance. Each operation accessing sensitive resources must be extended to call the security manager to check whether the operation is granted or not. Listing 4 provides an example how to access

the security manager. For new security checks, the method `checkPermission()` should be used. A custom permission is not part of the prototype implementation.

Summary

The sandbox prototype is build on top of the OSGi framework. It uses two of the provided extension points: manager implementation and custom condition. Additionally, the manager implementation is designed as an OSGi service. The service can be used for the permission control dialog. All those extensions are illustrated in the class diagram shown in Figure 23.

The implementations of the user stories belong to three different bundles based on the functionality. All three bundles have the same prefix "de.rcenvironment.core", because the sandbox prototype is part of the RCE framework. Firstly, the user prompt condition must be placed in a bundle with an extension to the system bundle (S2). Therefore, the bundle has the suffix of ".security.condition". The dialog prompting for undetermined permissions must be located in the same location as the condition. The manager service is stored separately from the dialog classes, due to the naming convention of RCE bundles. All GUI related classes of the permission control dialog are located in the bundle ending with ".gui.security". The bundle ending with "security" contains the manager service and concrete implementation.

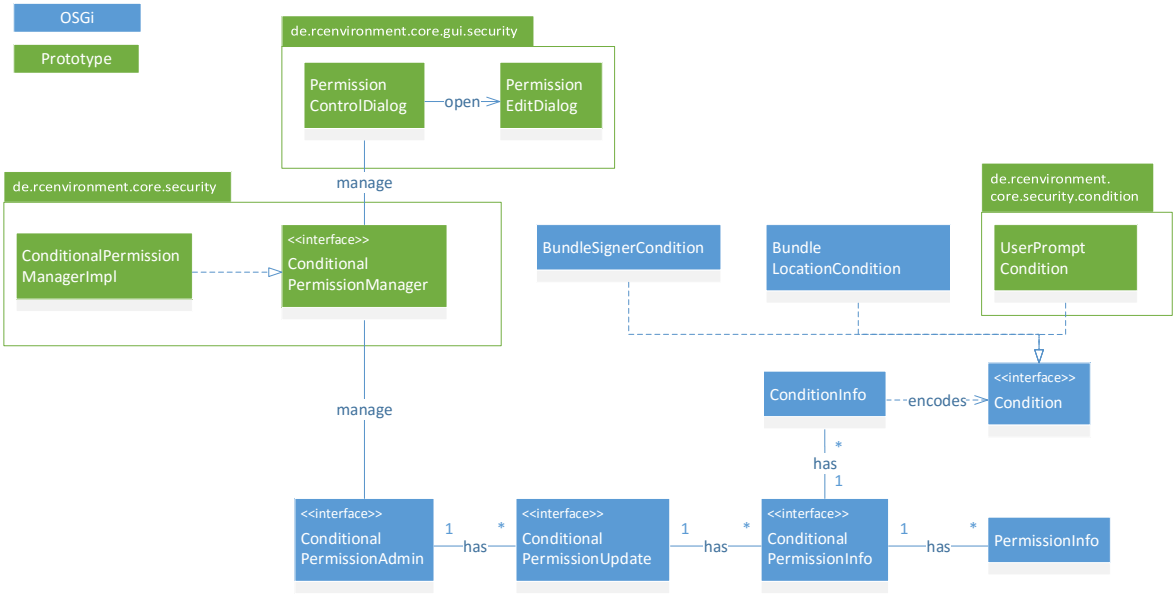

Figure 23: UML Class diagram prototype design

4.5.2 Implementation

The implementation of the sandbox prototype is based on the above described concept. RCE provides several workflow components. Input Provider and Script component are focused on during the implementation. For both components, the maximum set of permissions are identified and defined in the local permission resources (I1). The logging results supported the identification of the maximum permissions. Default permissions are identified which are necessary to allow access to OSGi resources. Those include package, bundle, service and capability permission. Listing 10 provides a template of the standard entries for the local permissions.

```
# Allow importing and exporting of all packages
(org.osgi.framework.PackagePermission "*" "import,exportonly")
# Allow all bundle actions
(org.osgi.framework.BundlePermission "*" "provide,require,host,fragment")
# Allow requesting and publishing services
(org.osgi.framework.ServicePermission "*" "get,register")
# Allow capabilities
(org.osgi.framework.CapabilityPermission "*" "provide,require")
```

Listing 10: Local default permissions for the OSGi framework

Additionally to the standard permissions, specific permissions of a workflow component must added to the resource. Input Provider has the functionality to provide a file or directory as an output type. Hence, it requires read access to files and directories. All component write the processed data into the data management. Thus, the input provider component needs to be granted write access as well.

The Script component provides the execution of scripts. Thus, it may require a diverse set of permissions such as full access to the file system and connection to the network. Moreover, the logging results shows which permissions are requested by the script bundles. The script bundles requested the additional permissions: admin, property, reflect, topic, adapt and runtime. Those must be added to the local permissions set. Script component has three bundles responsible for the execution functionalities. Hence, each bundle must contain their own local permission resource.

The RCE launch configuration contains the VM argument to install the security manager of OSGi (R1). RCE framework is started through a `Application` class. The class is used to verify whether a security manager is installed by using the example of Listing 9. Additionally, the application class requests the manager service to initialize the policy table (R2).

Manager implementation

The manager implementation is realized as an OSGi service (S3). It uses the CPAS to manage the policy table of RCE. Therefore, it provides the methods shown in Figure 21. The method `initialize()` is responsible to add the permissions for the default groups to the policy table (R2). For the third permission group called standard, three permissions were intended on the design. However, during the execution of RCE with active sandbox further permissions are required. It includes the following three permissions which are added to the standard group: property, log and runtime permission. All those permissions are added without a condition to the policy table.

The Permission control dialog uses the manager service to display all workflow component bundles and their granted permissions (C1). The user stories of the data acquisition category are implemented through the `components()` (D1) and `grantedPermissionsFor(bundleName)` (D2) methods provided by the manager service. The design of the permission control dialog is based on the prototype shown in Figure 20. The administrator is able to add, edit and remove permissions for each bundle (C2-C4). All workflow components are granted the service permission by default. It appears in the permission control dialog. However, the administrator can not edit or remove a default permission.

Figure 24 shows the permission dialog implemented in RCE. The user story IDs necessary for the dialog are represented within the figure. For example, the control buttons to manage permissions (C2-C4) are located on the right side of the permission dialog (C1). The administrator has access to the permission dialog at any time. CPAS guarantees that all changes to the policy table are in real time. RCE provides access to the dialog via the tool bar and the file menu.

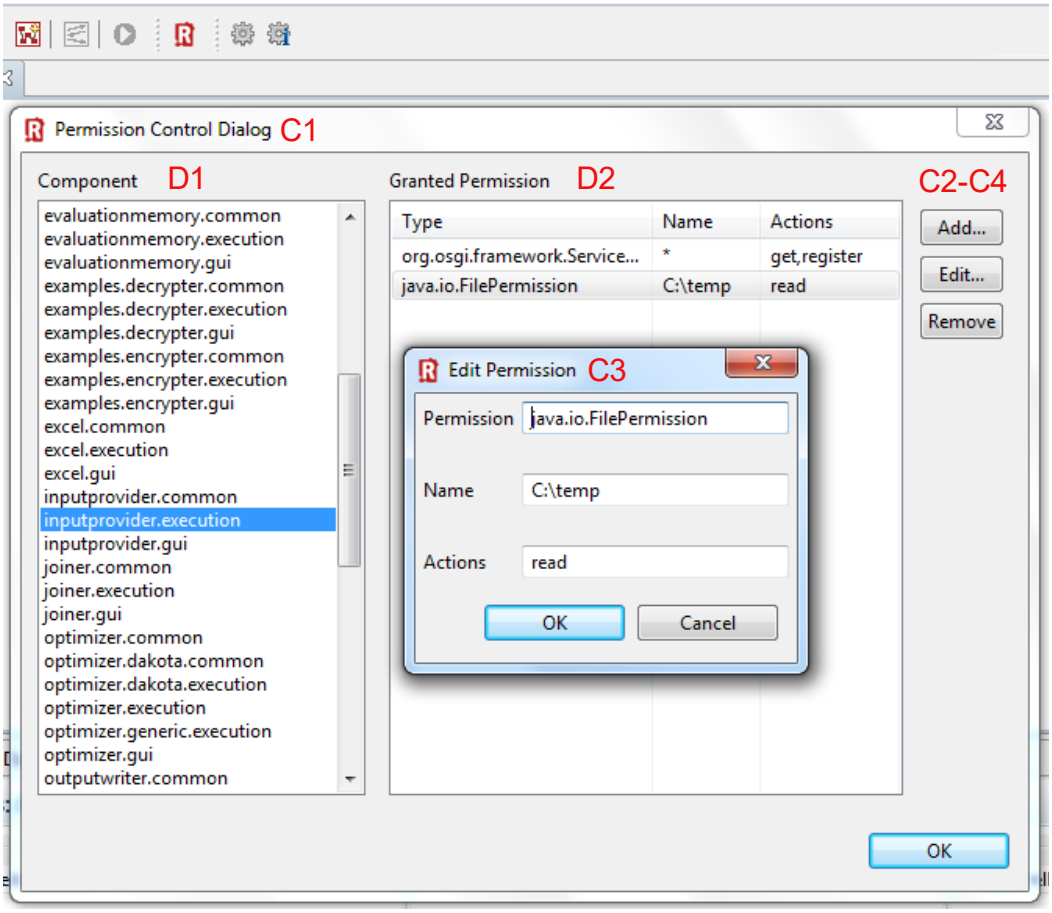

Figure 24: Permission Control Dialog (C1)

All workflow components need access to the data management including the Input Provider and Script component. There are two available approaches to grant the write access to the data management. First approach is based on granting a specific `FilePermission` with write access to all necessary bundles. The file permission requires the data management location as a path. The data management location is different depending on the operating system, installation directory and user profile. Hence, the dynamical path must be retrieved from the data management.

The privileged call provided by the Java Sandbox is a suitable second approach. All operations with direct access to the file system must be executed in a privileged call. Furthermore, the file permission must be granted to the data management bundle. Workflow components receive temporarily access to the file system by the privileged call. For the approach, all operations must be extended to check whether a security manager is installed and perform the actual access within a privileged call. However, it violates the requirement to implement the prototype without modifying existing code. Therefore, the first approach is implemented in the sandbox prototype. The privileged call approach is recommended for further improvements.

Both user stories from the persistent permissions category are not implemented in the prototype (P1-P2). Regarding the prototype, permissions must be granted again for each start of a RCE instance. Two opportunities are determined for further research. `SecurityAdmin`, a concrete implementation of the CPAS provided by Eclipse Equinox, has access to a reference of `PermissionStorage`. The purpose of the research is to find out either how to activate or how to use the storage to save and load the permissions persistently. The second opportunity is established by RCE. RCE offers a simple persistent key-value-store service called

`PersistentSettingsServices`. During the shutdown process of RCE, the services may be used to save all permissions added by the administrator (P1). The initialization of the policy table should restore the permissions and add them together with the default permissions to the policy table (R2).

Custom Condition

The purpose of the `UserPromptCondition` is to provide a good user experience. A workflow asks the administrator for granting a missing permission before terminating the workflow (W1). The effective permissions of a bundle are the intersection between the local and system permissions. Hence, the system permissions must grant the same specific permissions as determined in the local permission resource. Either those are explicitly granted by the administrator or the system prompts a dialog to allow or deny the permission.

In the last case, the specific permissions are added to the policy table protected by the `UserPromptCondition`. For example, specific permissions are file, socket or even runtime permissions. Each permission is added with a single action and a wild card as name to match all possible resources. Listing 11 contains encoded examples of the specific permissions guarded by `UserPromptCondition`.

```
1  ALLOW {
2    [UserPromptCondition "FilePermission" "<<ALL FILES>>" "read"]
3    (FilePermission "<<ALL FILES>>" "read")
4  } "1"
5  ALLOW {
6    [UserPromptCondition "FilePermission" "<<ALL FILES>>" "write"]
7    (FilePermission "<<ALL FILES>>" "write")
8  } "2"
9  ALLOW {
10   [UserPromptCondition "SocketPermission" "*" "accept"]
11   (SocketPermission "*" "accept")
12 } "3"
```

Listing 11: Specific permissions protected by the `UserPromptCondition`

The dialog requires a certain set of information to provide a message for the administrator which bundle requests a permission. The message requires the bundle name, permission type, name and action. However, a condition is unaware of the permission it protects. It only knows the bundle requesting the protected permission. Therefore, a user prompt condition contains the permission information as arguments as shown in the Listing 11. Based on the arguments, the dialog can display a message containing bundle name, permission type and action. The actual name of the resource cannot be displayed, because it is not provided to the condition. In order to provide a clear message to the administrator, a permission is added only with one action. Therefore, permissions providing several actions are added separately like shown with the file permission. Otherwise, a message could contain the file action read and write during a read access.

Figure 25 shows the user condition dialog during a workflow execution (W1). The message contains information about the Script component requesting a read access to a file. However, the message is not clear about which specific component of the workflow requests the permission. For example, a workflow contains several Script components. During a permission request, it is not possible to clearly assign a request to one specific Script component. Additionally, the user condition dialog is also prompted outside a workflow execution. For instance, the GUI bundle of a component requires file access.

The condition dialog is implemented in Swing, due to the limitation of the extension to the system bundle. The dialog itself must be created and displayed within a privileged call.

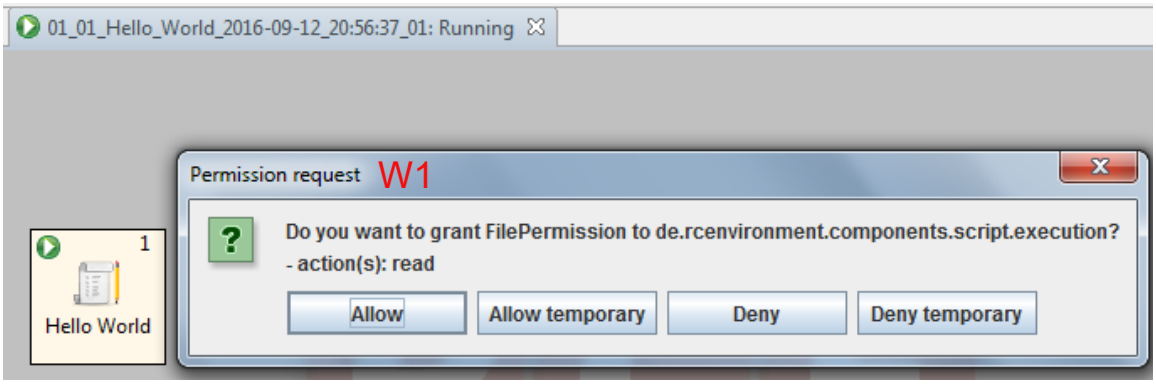

Figure 25: User prompt dialog

Otherwise, further security checks are caused by the Swing dialog. The condition belongs to the system bundle, thus it has the protection domain of the framework granted with `AllPermissions`.

The administrator can make a decision for the requested permission by choosing one of the four action buttons. Temporarily granting or denying the permission is provided by the second or fourth button (W2). A temporarily granted permission is only valid for one access to the resource. Afterwards, the dialog may be prompted again for the bundle requesting the same access. The first and third button represents a permanent decision to grant or deny the permission (W3). The condition changes from mutable to immutable when one of the permanent buttons is clicked. Hence, the decision result is cached and used for the same permission request. For permanent decisions, the dialog only appears once per bundle requesting a resource with a missing permission. A permanently denied permission can be reversed by granting the specific permission via the permission control dialog (C1). A permission granted permanently only results in caching the value. However, the granted permission is not added as a new entry to the policy table. Thus, the administrator cannot revoke the permission. Currently, only a restart of the RCE instance resets all cached values of the user conditions.

To successfully implement the user story (W3), the permission must be added to the policy table for granting it permanently. A considered approach is that the condition must add the permission by itself. In order to add the permission, the user condition must have access to CPAS and provide information about the permission. Firstly, the user condition is not allowed to import the manager implementation. It can request the CPAS directly from the system bundle. Nevertheless, during the request of CPAS an exception of a missing `AdminPermission` occurs. Granting the admin permission to each bundle does not solve the problem. No practical solution could be found to request the CPAS without causing a exception. Lets assume the CPAS can be successful requested. The provided arguments for the user condition would be sufficient to grant a permission. However, the permission grants access to a broader range of resources, due to the provided name containing a wild card. The actual name of the resource must be provided to restrict the permission allowing access only to the requested resource.

Summary

The sandbox prototype for RCE manages the system permissions using the CPAS provided by the OSGi sandbox model. The class diagram illustrated in Figure 26 summarizes the above described implementations. The permission control dialog makes use of the provided `ConditionalPermissionManager` service. The class `GrantedPermission` encapsulates permission information to be displayed in the permission control dialog. Additionally, it contains information whether a permission is editable or not.

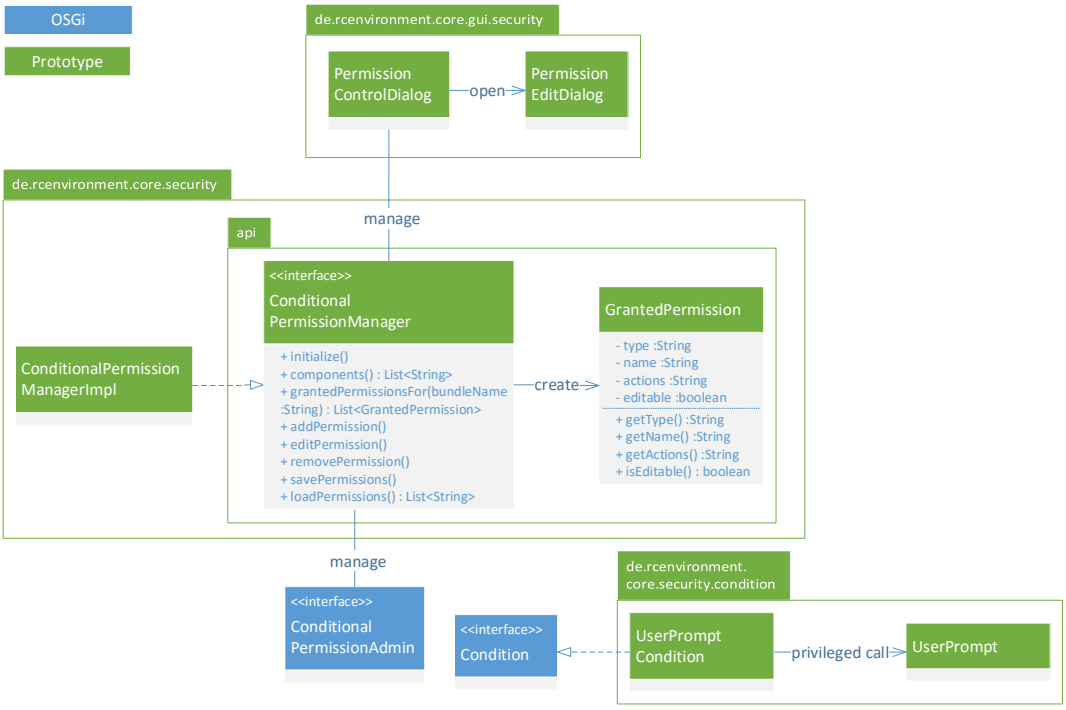

Figure 26: UML Class diagram prototype implementation

To summarize, the sandbox prototype for RCE is successfully implemented. Table 10 contains all user stories with the corresponding priorities and status. Three of the user stories (W3, P1-P2) could not be implemented as discussed above. Other requirements which are not part of the product backlog are satisfied. Firstly, new bundles are created for the sandbox implementation. Existing code was only modified to initialize the sandbox. Additionally, bundles of the Input Provider and Script component are supplemented with a local permission resources. Lastly, the source code of the sandbox complies with the **E**clipse **P**ublic **L**icense.

4.6 Framework architecture

The objective was to implement a sandbox prototype build on top of existing features. The overall framework architecture of RCE is comprised of Java, Eclipse RCP and the software layers of RCE itself. Java provides the foundation of the sandbox model with the security manager and permission concept. The **C**onditional **P**ermission **A**dmin **S**ervice is provided by the OSGi sandbox model. Additionally it introduces the condition approach. The sandbox prototype adds a new software layer to the RCE framework as illustrated in Figure 27.

The new security layer provides the sandbox of RCE. For the permission management of RCE, the security manager and CPAS of OSGi is used. Furthermore, the sandbox provides am OSGi service called `ConditionalPermissionManager` to manage the system wide permissions. All layers above and the GUI can request the service to manage the permissions. The administrator can use the established `PermissionControlDialog` to administer the permissions for each worklfow component. To interact with the administrator for missing permissions, the `UserPromptCondition` is introduced which displays a user prompt dialog.

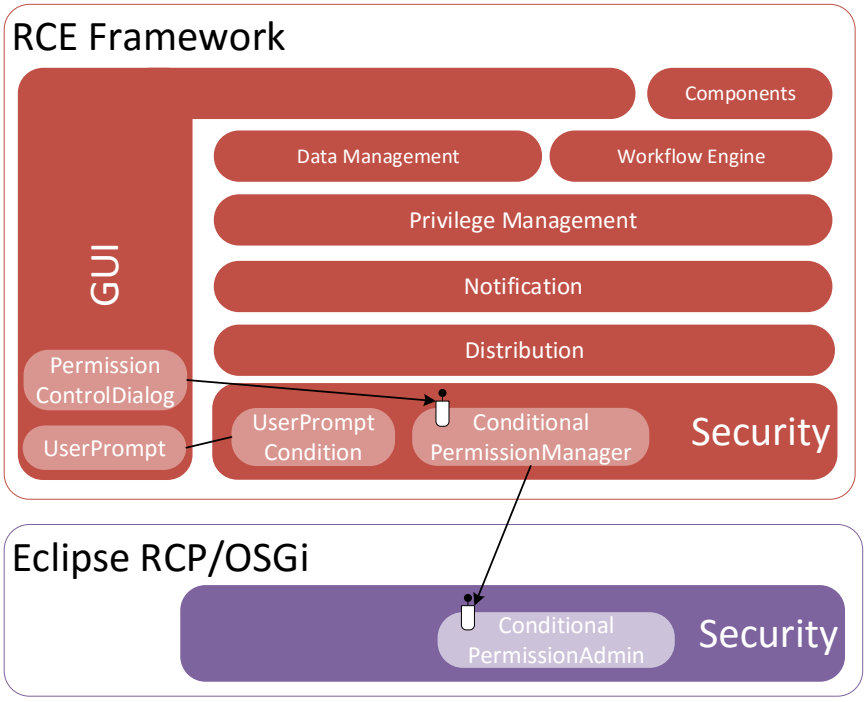

Figure 27: RCE Framework with the new security layer [SFL+12]

5 Evaluation of the sandbox prototype

This chapter evaluates the impact of the implemented sandbox prototype on security and user experience. For this purpose, three test workflows are designed using the Input Provider and Script component. The prototype implementation only focused on these two components, due to the complexity of the RCE framework and large number of provided standard components. Hence, local permission resources are exclusively created for the Input Provider and Script component.

Test cases are described to ensure correct operation behavior of the prototype. Each test case contains the execution steps that must be performed to achieve the expected result. Expected results are the execution outcome of workflows or permission requests for missing permissions. Those test cases are grouped into test suites to evaluate similar aspects like the appearance of permission request dialogs, execution of local and remote workflows. Test suites contain a short description and preconditions for the performance of the test cases. The actual results are compared and evaluated with the expected result for each test case.

The test suites and the results provided in Appendix A.5 (page 63) show the impact on security and user experience. However, the sandbox prototype has limitations in the execution of workflows. Not all test cases are executed successfully. Especially, workflows executed on a remote instance and workflows with connected components terminate in an error due to insufficient permissions.

5.1 Security

The effect of the prototype on security is tested by the first two test suites. Hence, workflows are executed locally and remotely with and without granted permissions.

The Input Provider component is configured with a file output during the test cases. Therefore, it requires access to a particular file. The permission request dialog is always prompted successfully if the file permission is not granted to the component. The dialog is only shown once for a permanent decision. However, the permission granted by the permission request dialog is too comprehensive. It provides access to all files. Thereby, granting the permission permanently for one file also allows the component to access any other file resource on the system. In terms of security, the permission should only allow the access to the requested file. To match all file resource requests the user prompt condition must protect the permission of all file accesses. In conclusion, the permission should only be used to match and set off the dialog. Another permission should ony be granted with a specific file resource. The workflow is only executed successfully if the permission is granted. Thereby, the prototype restricts effectively the Input Provider component to access the file without the permission.

The Script component contains a script which prints a string on the RCE console. This operation does not indicate a security-relevant access to resources. However, the script execution requests access to seven different resources. The script is executed with Jython and Python, while Jython is only executed successfully. Nevertheless, the permission are still requested by Python, but it fails due to an unidentified permission. Hence, the sandbox constrains Python to execute scripts even with identified permissions granted.

The sandbox is very restrictive during the execution of connected components and on a remote instance. A workflow connects the Input Provider together with a Script component. The Input Provider loads and sends a file to the Script. Previously the Input Provider had only requested access to read the file, but it requires write access to forward the file to another component. The workflow fails due to missing permissions of the Script component, although the component requested seven permissions for the execution. During the execution of workflows

on a remote instance a similar behavior is observed. The workflows fails in all test cases due to an unidentified permission. Hence, the prototype requires adjustment to grant necessary permissions for previous cases.

In summary, it can be stated that the execution of workflows is limited if the necessary permissions for the individual workflow components are unavailable. Therefore, the security of RCE can be improved by the sandbox prototype. However, normal features such as connected components and remote workflow executions are negatively affected by the sandbox. Missing permissions are requested whether they should be granted or not. Granting those permissions permanently allows access to a wide range of resources, thus reducing the security of the permission management.

5.2 User experience

The term user experience has been explained in section 4.1.1. The sandbox prototype introduces the administrator role. Hence, the experience of the user and administrator interacting with RCE needs to be described. The interaction with RCE can be influenced by the sandbox in the following manner: interruptions by permission request dialogs, delay of workflow execution or termination due to an error.

The user interaction with RCE is the design and execution of workflows. Therefore, the sandbox can affect the experience negatively by delaying or failing the workflow execution. Responsible for managing permissions is the administrator. Hence, the administrator has to deal with the interruption of permission request dialogs. He makes either a temporary or permanent decision for the requested permissions. The effect of the decision for the user experience is evaluated by the third test suite.

A workflow component requests access to a system resource and could display a dialog for a missing permission. While the dialog is shown, the workflow execution is delayed. This permission can be granted or denied by the administrator. Thereby, the decision can be made temporary or permanent. On the one hand, a permanent decision displays the dialog only once. Hence, RCE remembers the decision and either grants or denies the specific resource without showing the dialog again. For the Input Provider component in the test cases only one dialog is shown to access the file. After granting it permanently RCE remembers to grant the permission for the same component. On the other hand, a temporary choice is only valid for one access to a resource. The dialog keeps reappearing until the access to the resource is completed. In this case the experience of the administrator with RCE is impacted negatively. As shown in the test suites the dialogs appear several times when granting it temporarily. For the Input Provider the dialog is displayed three more than when granting permanently. The Script component produces even over 100 permission request dialogs.

In conclusion, the security improvements enforced by the sandbox effects the user experience mostly negatively. The permission request dialogs delay the workflow execution. Additionally, denied permission results in a failed workflow. The advantage of permanent decision for the user experience is that RCE remembers which permission is allowed or denied. After a while of using RCE less dialogs are prompted. However, granting permissions temporarily requires the confirmation repeatedly.

6 Conclusion and Future Work

The RCE framework is based on RCP which implements the Java framework OSGi. RCE provides workflow components to create a simulation of a complex system. The components are executed in a so-called workflow either local, remote or combined. RCE grants full access to system resources. Consequently, RCE is vulnerable to malicious code contained in a remote component. The system security should be increased by providing an access control. The general purpose of access control is to control and restrict access to system resources. The following three isolation techniques have been analyzed to secure potentially RCE against the execution of malicious code: Hypervisor-based, Container-based and Sandbox-based isolation.

The analyzed techniques provided different approaches to protect a system from damage during the execution of remote code. The hypervisor-based and container-based technique establishes a virtual environment of different scope for the execution of code. The isolation inherent in the virtual environment protects the system for damage. Only the sandbox-based technique provides an access control based on a security policy. Additionally, Java has a build-in sandbox model. Hence, a sandbox prototype has been implemented to examine whether it is an effective technique to secure RCE.

The objective of the thesis was to design and implement a sandbox prototype for RCE. OSGi provides an extension to the Java sandbox model to manage permissions based on conditions in real-time. OSGi established a service for the permission management. In addition, extension features are offered to create custom permissions and conditions. The sandbox prototype uses the provided service of OSGi to manage the permissions in RCE. Additionally, the prototype adds a dialog to configure the permissions by the administrator. A custom condition is implemented to display a dialog for missing permissions, thus an administrator can grant or deny the permissions.

The identification of elements accessing system resources showed a high amount of permission requests. Therefore, a security policy can effectively be implemented with the sandbox to ensure granted access to resources. It helps to secure the RCE framework.

The final evaluation shows that the sandbox prototype prevents the execution of workflows without the required permissions. Thereby, RCE offers more security against the execution of malicious code. However, the prototype restricts the execution of workflows on a remote instance or with connected components. Apparently the execution on the network and for connected components requires additional permissions which have not been identified. The sandbox prototype requires precise adjustments for providing the appropriate amount of permissions to execute RCE. The user experience is affected by the approval or disapproval dialog of missing permissions.

In conclusion, the implemented sandbox prototype for RCE proves that sandbox is an effective technique to secure the RCE framework. Finally, an outlook for further developments of the sandbox will be discussed in the following section introduced.

Future Work

The sandbox prototype focuses on protecting the system resources. Thereby, access to sensitive resources established by RCE are unprotected. Custom permissions can encapsulate the access to those resources of RCE. For instance, data management access could be represented by a `DataManagementPermission`. Access control should be performed to decide whether an operation for the resource is granted or not. Hence, confidential data stored on a remote RCE instance can be access protected without permission.

The execution of workflows with missing permissions can result in delay or even leads to an early termination. RCE instances in a network can be configured to grant different sets of permissions to workflow components. To avoid delays or termination of workflows a RCE instance should provide status information about the sandbox in the network. An instance should indicate whether it has started with the sandbox. Additionally, it should show which permissions are granted for certain workflow components. Then, instances can be selected based on the appropriate permissions provided for the execution. Otherwise, the workflow can be adapted to the limitations of the execution environment.

The security layer of RCE can be supplemented by user authentication and authorization. Therefore, OSGi provides the role-based User Admin Service. Bundles can request the service to verify whether a user is authorized [HPMS11]. The service can be used to introduce the user and administrator role to RCE. Only the administrator role receives access to the permission control dialog. Furthermore, the visibility of entries in the data management or workflow components can vary based on a role.

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A Appendix

A.1 Sandbox classes summary

The class diagram 28 shows all Java classes which are helpful to understand the Java sandbox model.

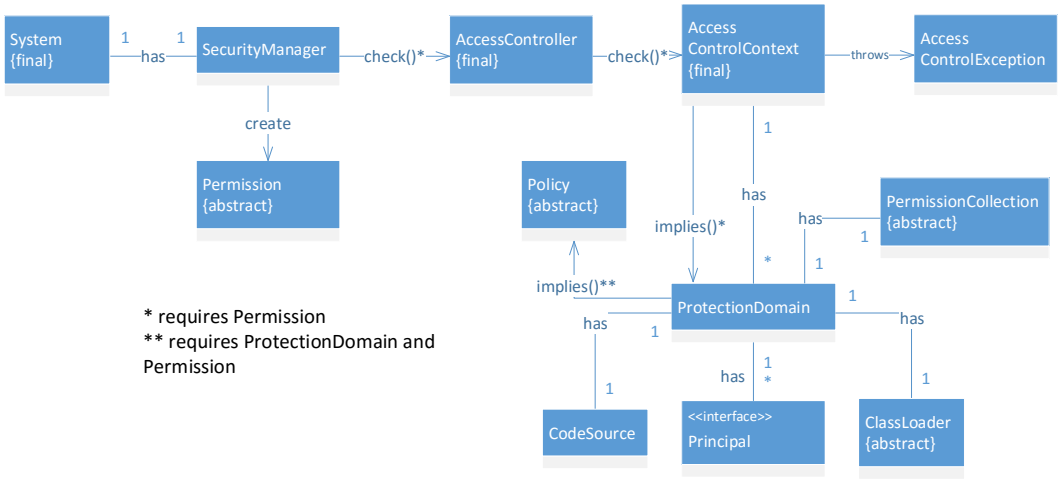


Figure 28: UML class diagram of the Java 2 Sandbox model

Table 9 contains all Java classes and interfaces of the Java sandbox model. It provides the package, name, usage and the JDK introduction version.

Package	Interface/Class Name	Usage	JDK
java.lang	ClassLoader	Loads classes from byte code	1.0
	SecurityException	States a security violation	
	SecurityManager	Mediates all access control decisions	
	System	Activates the SecurityManager	
java.security	AccessControlContext	Makes system resource access decision based on the context	1.2
	AccessControlException	States a denied access request	
	AccessController	Makes access control operations and decisions	
	CodeSource	Encapsulates the location (by URL) and the certifiactes of the code	
	Permission	Represents the access to a specific resource	
	PermissionCollection	Represents a homogeneous collection of Permission objects	
	Permissions	Represents a heterogeneous collection of Permission objects	
	Policy	Encapsulates the security policy	
	Principal	Represents an entity	
	ProtectionDomain	Represents a unit of classes which are granted with the same permissions	
	SecureClassLoader	Adds secure methods to load classes	

Table 9: Provided Java classes of the default sandbox model

A.2 Developer instruction (user story I1)

A developer can follow the following instruction for setting up *local* permissions for a bundle.

Developer instruction

Configuring local permissions

Before starting with the configuration of the local permissions for your bundle, make sure you have checked out RCE and you are able to run it. Otherwise, start first with the developer guide how to get started with RCE. Familiarize your self with the permission concept and identify the amount of permissions your bundle will ever use.

Note

Local permissions determine a maximum set of permissions a bundle can be granted.
A bundle is granted `AllPermission` if the permission resource is missing.

Instruction:

1. Create the permission resource named "permission.perm" in the folder *OSGI-INF* of your bundle
2. Open the "permission.perm" resource
3. Add new permission entries to the permission resource.

   Default permission resource syntax
   permissions ::= ('(' type [qname [qactions]] ')')+
   qname ::= '"'name'"'
   qactions ::= '"'actions'"'
   actions ::= action | action','actions
   type ::= string-permission-class-type
   name ::= string-permission-name
   action ::= string-permission-action

   ---

4. Save permission resource
5. Start RCE and see if your bundle receives enough permissions

Example permission resource:

```
1  # Allow import and export of packages
2  (org.osgi.framework.PackagePermission "*" "import,export")
3  # Allow to access services
4  (org.osgi.framework.ServicePermission "*" "get")
5  # Allow access to all files
6  (java.io.FilePermission "<<ALL FILES>>" "read,write")
```

A.3 Logging result

The log results contain all requested permissions during the execution in the project environment of three RCE instances. The following two figures shows filtered results of the log files. The filter is set to only show bundles which requested the `SocketPermission`. Client 1 and 2 requested 27 times the permission. On the other hand, socket permission was request 65 times by the server instance as described in Table 7. The first figure shows the bundles of both clients, because the results are identical. Figure 30 shows the distribution of requests of the server instance. Both figures show similar bundles which also have the same request amount such as *configuration* and *shutdown*. The network connection of the server may be the reason for the higher amount of socket permission requests.

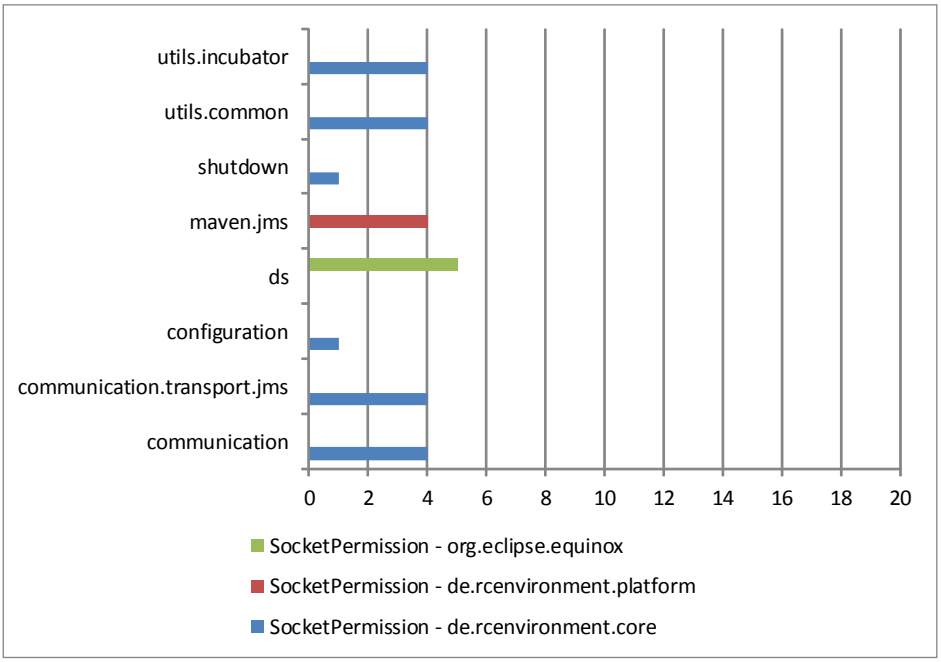


Figure 29: Client 1 and 2: Bundles requesting socket permission

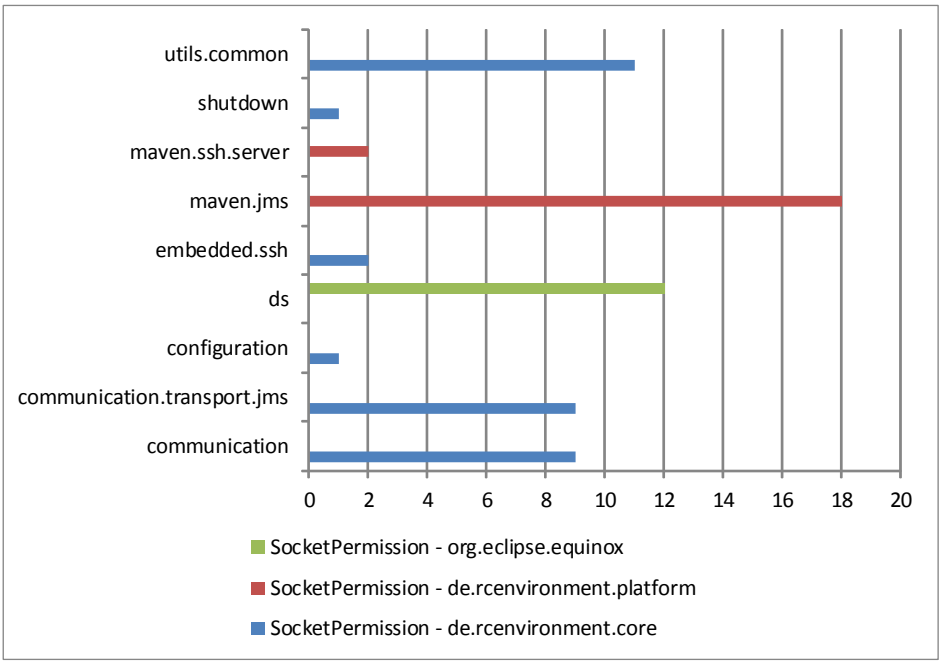


Figure 30: Server: Bundles requesting socket permission

A.4 Final product backlog

Requirements are described as *User stories*. All user stories are planed for the implementation of sandbox prototype and initial receive the status *TODO*. User stories describing functional requirements are illustrated as *Use case*s in the Section 4.5. Each user story is prioritized by applying the *MusCoW* method. The method has three categories: *Must*, *Could* and *Wish*. User stories rated with *Must* are essential to achieve the objective of implementing the sandbox prototype. The category *Cloud* includes user stories describing relevant features which are not necessary for the success. The prototype is limited in the usability without those user stories. The implementation of user stories indicated with *Wish* are desirable. The prototype works without limitation, when those user stories are missing.

Table 10 shows the final product backlog. An additional column shows the status after the sandbox implementation for each user story. Usually, user stories may be in one of the following status: *TODO*, *IN PROCESS*, *TO VERIFY* and *DONE*. In this case, only *TODO* and *DONE* are used to indicate the success of the prototype implementation. Therefore, a user story receiving the status *TODO* could not be implemented. On the other hand, *DONE* shows that the user story is successful implemented.

ID	User Story	Priority	Status
Instruction			
I1	Developer follows an instruction about specifying maximum bundle permissions	Must	DONE
RCE start configuration			
R1	RCE starts with active security mechanism	Must	DONE
R2	RCE grants default permissions	Must	DONE
Data acquisition			
D1	RCE loads all bundle names of workflow components	Must	DONE
D2	RCE loads granted permissions for a workflow component	Must	DONE
Configuration			
C1	RCE provides a dialog for configuring permissions for workflow components	Must	DONE
C2	Administrator grants permission for a workflow component	Must	DONE
C3	Administrator edits granted permissions of a workflow component	Must	DONE
C4	Administrator revokes permission for a workflow component	Must	DONE
Workflow execution			
W1	RCE shows a dialog for undetermined permissions	Must	DONE
W2	Administrator makes a temporary decision for an undetermined permission	Must	DONE
W3	Administrator makes permanent decision for an undetermined permission	Could	TODO
Persistent permissions			
P1	RCE saves granted permissions persistently	Wish	TODO
P2	RCE loads persistent permissions	Wish	TODO
Spike stories			
S1	Research and describe Java Sandbox Model	Must	DONE
S2	Research and describe OSGi Sandbox Model	Must	DONE
S3	Research about OSGi Service	Must	DONE

Table 10: Final Product Backlog

A.5 Test suites

The evaluation is performed by executing the following three test suites. The test suites describe several test cases either executing a workflow or reacting on a permission request dialog. Only the *Input Provider* and *Script* component are considered during the design of a workflow. The first two test suites evaluate the effect of the sandbox prototype on security. The last test suite has the focus on the user experience and thus, the appearing dialogs are counted.

Test suite 1

Description

The test suite evaluates the effects of the sandbox prototype in RCE on the execution of workflows. For evaluation purposes workflows are executed on a single RCE instance. The test cases describe the execution of the following workflows:

Workflow 1 contains one *Input Provider* component. The Input Provider provides outputs for other components with different data types such as integer, boolean and file. A file output is configured for the component. Workflow 2 contains one *Script* component. A script can be programmed and executed with Python or Jython. A script is programmed to display a string in the RCE console. Workflow 3 contains one *Input Provider* and one *Script* component. The Input Provider component provides a file to the Script component. The Script component displays the content of the file in the RCE console.

Precondition

1. A RCE instance is started with active sandbox.
2. A new project is created.
3. A text file called "input" is created with the content "RCE sandbox".
4. A text file called "readme" is created with the content "Keep reading".
5. A new workflow called "Workflow 1" is created with an *Input Provider* component and the "input" file is configured as output.
6. A new workflow called "Workflow 2" is created with a *Script* component and the script displays the string "Hello World".
7. A new workflow called "Workflow 3" is create with an *Input Provider* and the "input" file is configured as output. The workflow contains a *Script* component connected to the Input Provider. The script displays the content of the file.
8. The administrator does not provide additional permissions for the components.

Test case 1

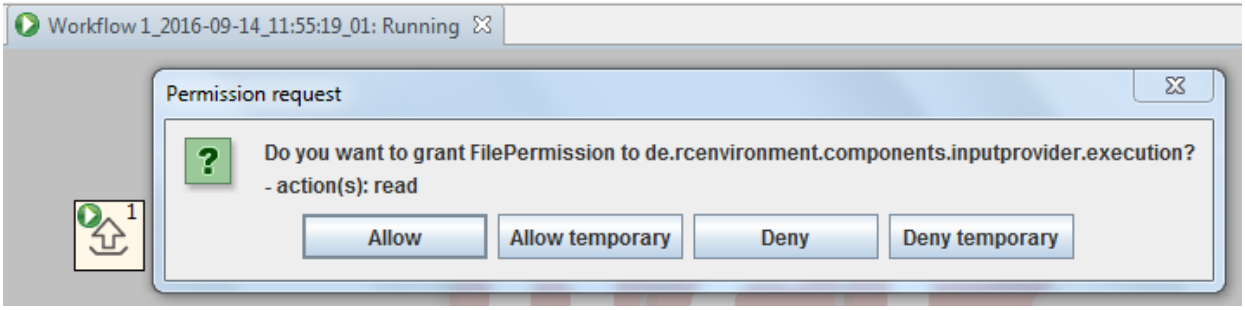
Description: Workflow 1 is selected and executed.

Expected results: During the workflow execution, the Input Provider accesses the "Input" file and a security check is triggered with the following parameters:

The Input Provider is currently not granted with the file permission. Therefore, a dialog is prompted to grant the file permission with read access to the bundle. The dialog provides information about the bundle name, permission type and action.

Bundle name	de.rcenvironment.components.inputprovider.execution
Permission type	FilePermission
Permission name	Path to the "input" file
Permission action	read

Actual results:



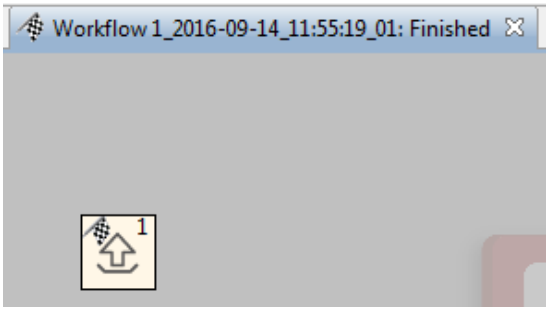
Evaluation: The dialog message contains the correct information.

Test case 2

Description: The file permission for the Input Provider component of Workflow 1 is granted permanently.

Expected results: The Input Provider receives access to the file. The workflow successful executes.

Actual results:



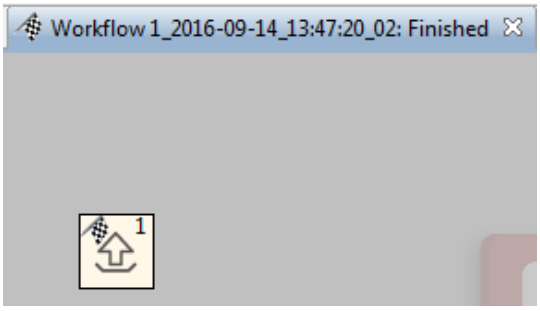
Evaluation: The Input Provider component is granted access to the "Input" file and the worklfow is successfully executed.

Test case 3

Description: The Workflow 1 is executed again. From the previous execution, the permission to access the "input" file is already granted.

Expected results: The workflow executes successful without prompting a dialog to grant the file permission.

Actual results:



Evaluation: The workflow is granted the file permission and is executed successful.

Test case 4

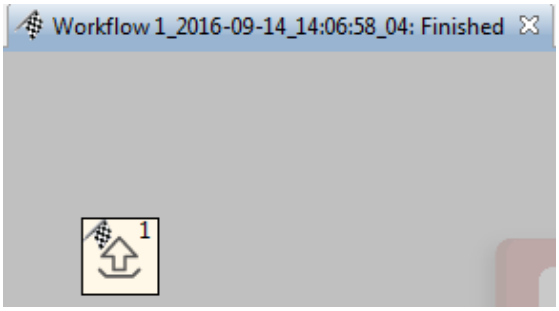
Description: The file output of the Input Provider is changed to the "readme" file. Afterwards, the Workflow 1 is executed.

Expected results: A dialog is prompted again, because the Input Provider is granted the file permission only to access the "input" file. Therefore, a dialog is prompted again for granting the permission to access "readme". The security check contains the following information:

Bundle name	de.rcenvironment.components.inputprovider.execution
Permission type	FilePermission
Permission name	Path to the "readme" file
Permission action	read

The dialog message contains information about bundle name, permission type and action.

Actual results:



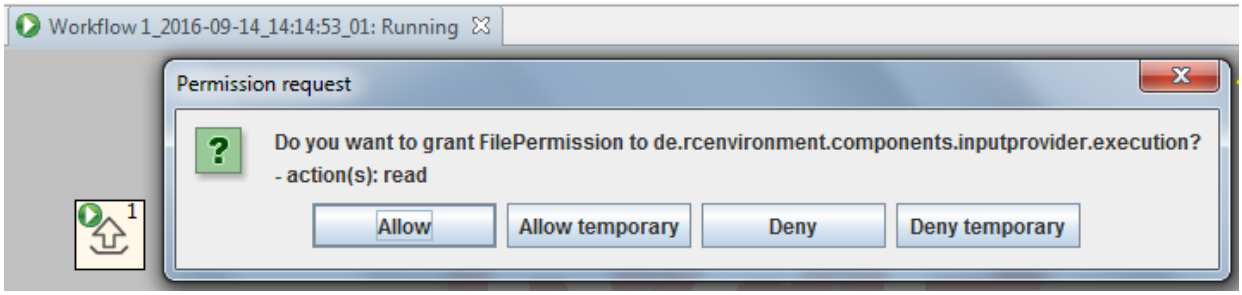
Evaluation: The workflow executes successful without prompting a permission request dialog. Thus, the file permission is granted to the bundle regardless of the actual resource.

Test case 5

Description: The RCE istance is restarted to reset the permanently granted file permission to the Input Provider. The Workflow 1 is executed with the file output "readme".

Expected results: A permission request dialog is prompted with the same expected information as described in Test Case 4.

Actual results:



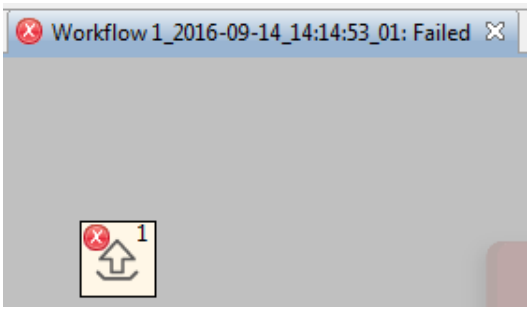
Evaluation: The dialog is prompted and displays the correct information.

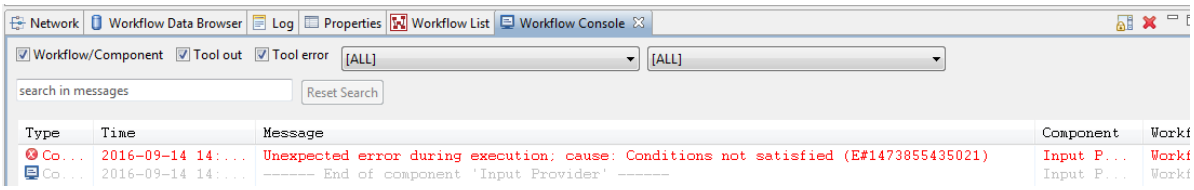
Test case 6

Description: The file permission for the Input Provider is permanently denied.

Expected results: The workflow fails, due to the missing file permission.

Actual results:



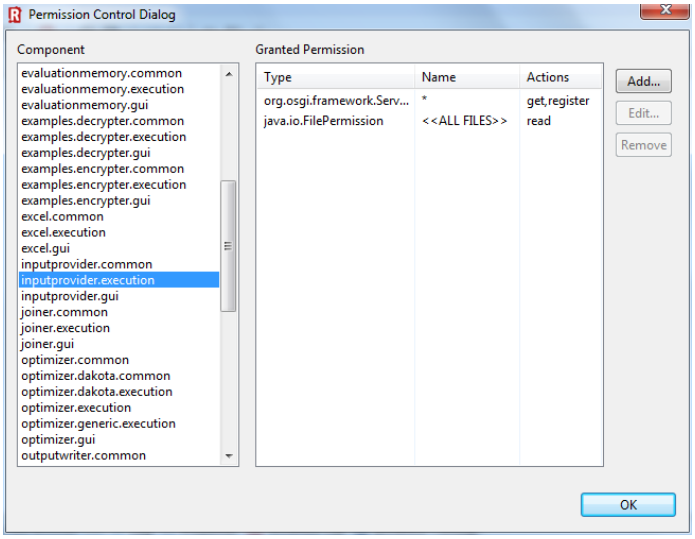


Evaluation: The workflow failed during the execution. An error occurred, because the permission request dialog represents a condition and it is not satisfied. Therefore, the access to the "readme" file is denied.

Test case 7

Description: A general file permission is granted to the Input Provider by using the permission control dialog. The general file permission contains the following entries:

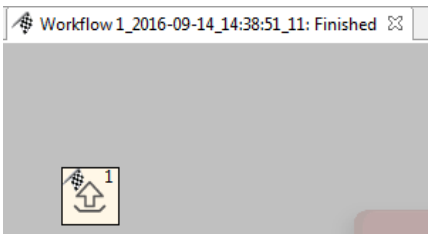
Permission type	java.io.FilePermission
Permission name	<<ALL FILES>>
Permission action	read



Afterwards, Workflow 1 is executed.

Expected results: The workflow successfully executes, because it is explicitly granted the file permission to access all files.

Actual results:



Evaluation: Workflow 1 is executed successfully.

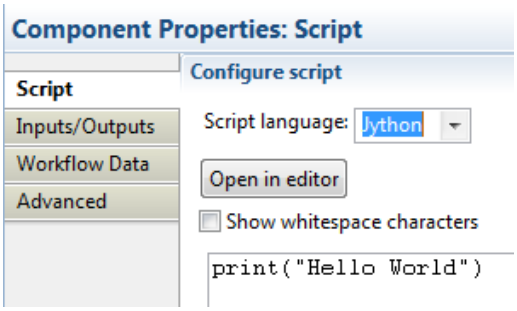
Test case 8

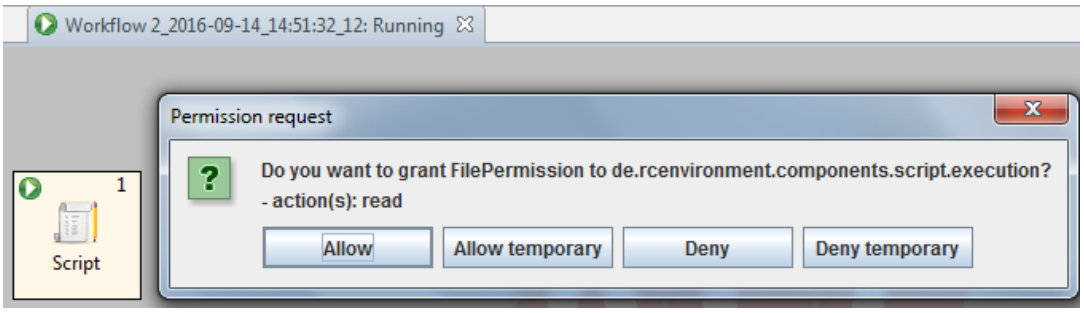
Description: Worklow 2 is selected. Jython is selected as script language for the Script component. Workflow 2 is executed.

Expected results: The workflow executes successful without prompting a permission request dialog. It prints "Hello World" to the RCE console. The code of the script does not indicate access to a sensitive resource.

Actual results:

Evaluation: Workflow 2 requested read access to a file. This might be caused by the execution of the script regardless of the code.



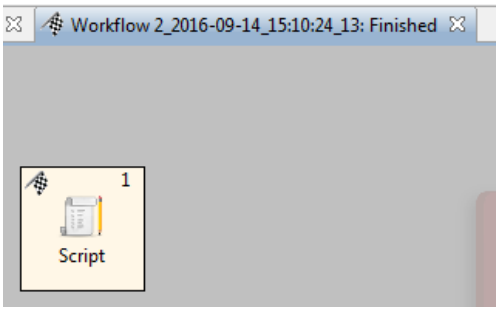


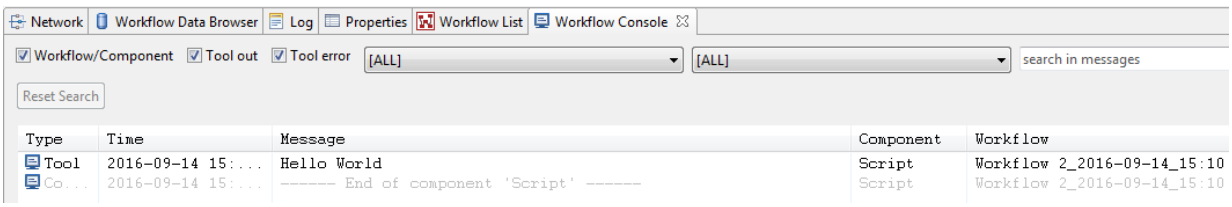
Test case 9

Description: The file permission for the script execution is granted permanently. All follow-up dialogs are necessary for the execution, therefore, they are granted permanently.

Expected results: After granting all permissions for the script execution, Workflow 2 executes successful and prints "Hello World" to the RCE console.

Actual results:



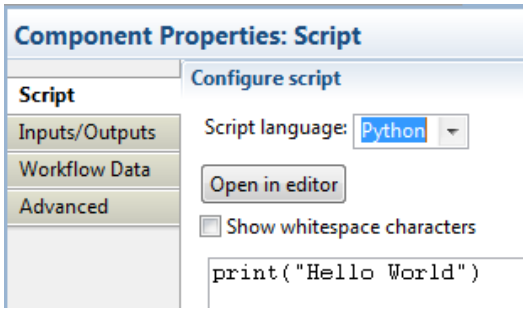


Evaluation: Six follow-up permission request dialogs appeared in the following order: The bundle names start all with *de.rcenvironment.components*. After granting all 7 permission requests, Workflow 2 successfully executed and printed out "Hello World" to the RCE console.

Bundle name	Permission type	Permission action
script.execution.jython	File permission	read
script.execution	File permission	write
script.execution.jython	File permission	write
script.execution.jython	Runtime permission	
script.execution	Runtime permission	
script.execution	File permission	delete

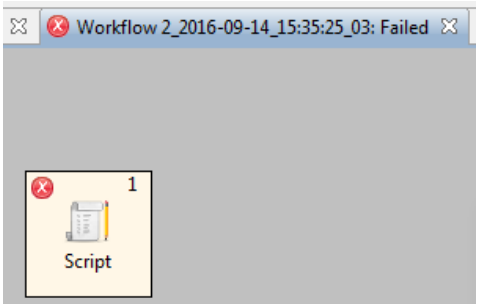
Test case 10

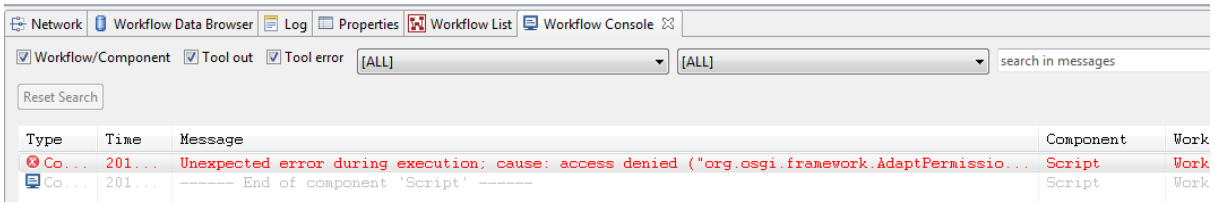
Description: The script language of the Script component is changed to Python and Workflow 2 is executed. Each permission request is granted permanently, because they are required for the execution of the script.



Expected results: The Script component requests permission to execute the script with Python. Jython requested in total 7 permissions. Python may request around the same amount of permissions. After granting the missing permission, Workflow 2 finishes successful and prints "Hello World" to the console.

Actual results:





Evaluation: The execution of the Script component requested the following permissions:

Bundle name	Permission type	Permission action
script.execution.python	File permission	read
script.execution.python	File permission	write
script.execution.python	Runtime permission	
script.execution.python	File permission	delete

However, the workflow failed after granting those four permissions. An error occurred because of a missing adapt permission.

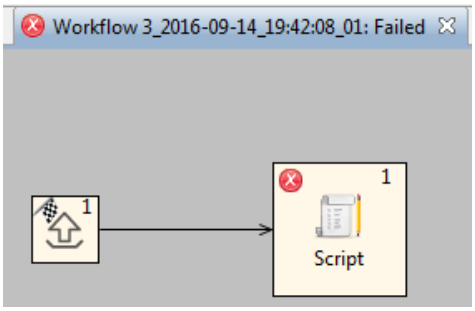
Test case 11

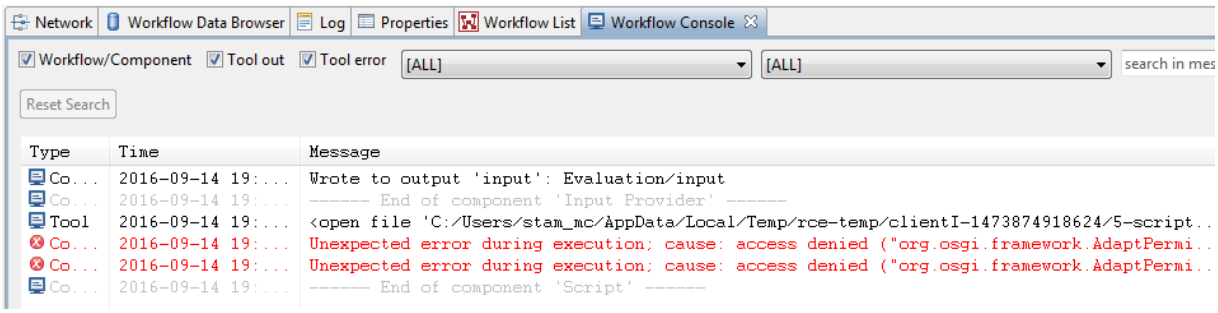
Description: Worklow 2 is selected. Jython is selected as script language for the Script component. Before executing Workflow 2, RCE is restarted to reset all granted permissions. All permission requests during the executions are permanently granted.

Expected results: The Input Provider component requests access to the "input" file. The Script component requires 7 permissions for the execution of the script as described in test case 9.

The workflow executes successful when granting the missing permissions. Additionally, the content of the file is printed to the RCE console.

Actual results:





Evaluation: The Input Provider component ends successful by providing the "input" file to the script component. During the execution, the Input Provider requested a read and write file permission. The write permission may be relevant for providing the file as output to the Script component. The Script component required the same permissions as described in test

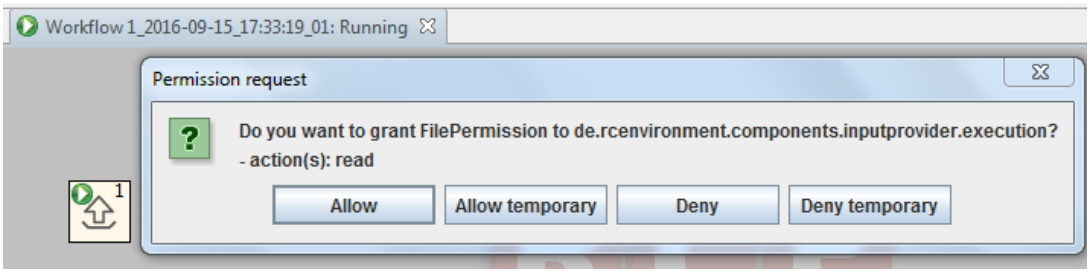
case 9. However, the component and also the workflow failed, due to access deny caused by two missing adapt permissions.

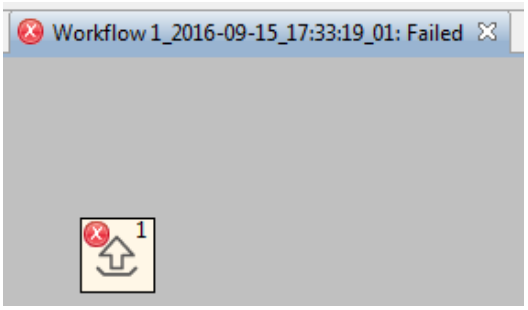
Test case 12

Description: Workflow 1 is executed after the restart of the RCE instance. The permission request for accessing the file is temporarily denied.

Expected results: The execution of Workflow 1 prompts one permission dialog request. The workflow fails after temporarily denying the permission.

Actual results:





Evaluation: The workflow prompted one dialog and failed, due to the denied permission.

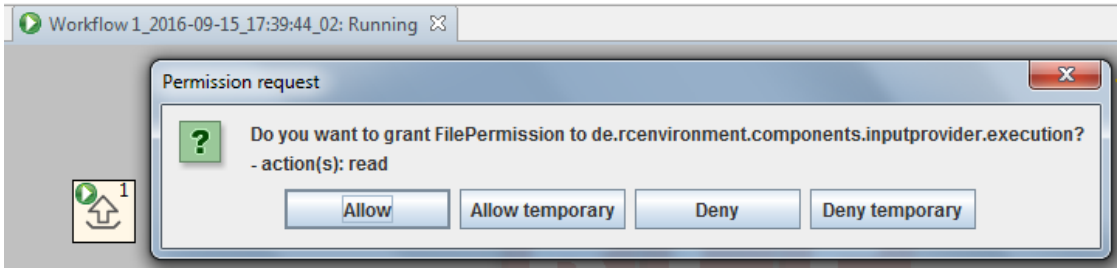
Test case 13

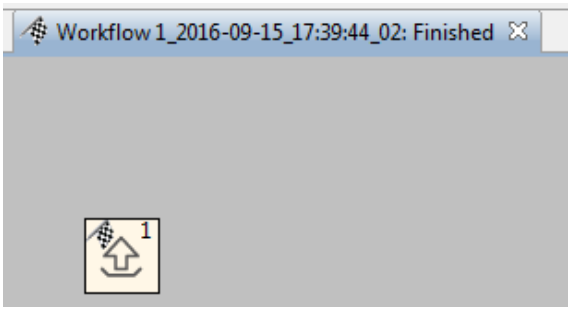
Description: Workflow 1 is executed again and requeste permissions are granted permanently.

Expected results: It should prompt a permission request again, because the test case before only denied the access temporary. The workflow finishes successful after granting the permission.

Actual results:

Evaluation: The permission request is prompted again and the workflow is executed successful.





Test suite 2

Description

The test suite evaluates the effects of the sandbox prototype in RCE on the execution of workflows in a project environment. For evaluation purposes workflows are executed on a client and server RCE instance. The test cases describe the execution of the following workflows:

Workflow 1 contains one *Script* component. A script can be programmed and executed with Python or Jython. A script is programmed to display a string in the RCE console. Workflow 2 contains one *Input Provider* component. The Input Provider provides outputs for other components with different data types such as integer, boolean and file. A file output is configured for the component.

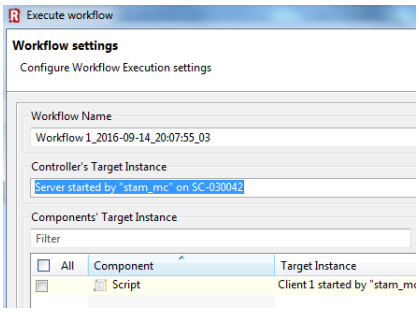
Precondition

1. A RCE instance is started as a server with active sandbox. The server must be started with a GUI to display the permission request dialog.
2. A RCE instance is started as a client with active sandbox.
3. The client is connected to the server.
4. A new project is created.
5. A text file called "input" is created with the content "RCE sandbox".
6. A new workflow called "Workflow 1" is created with a *Script* component and the script displays the string "Hello World".
7. A new workflow called "Workflow 2" is created with an *Input Provider* component and the "input" file is configured as output.
8. The administrator does not provide additional permissions for the components.

Test case 1

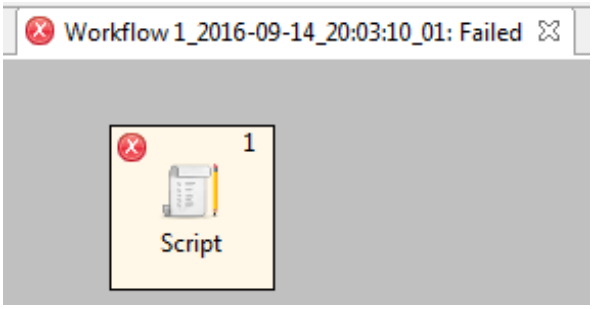
Description: Jython is selected as script language for the Script component. The workflow is executed on the server instance and the Script component is executed on the client. Workflow

1 is executed and all missing permissions are granted.



Expected results: The Script component requests 7 missing permissions on the client instance, because the component is executed on the client. Only the workflow is managed at the server instance. The worklfow executes successful and print the Script content to the console.

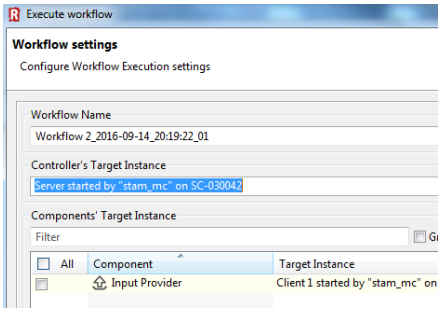
Actual results:



Evaluation: The Script component requested 7 missing permissions at the client instance. However, after the permissions are granted the component and the whole workflow failed, due to a missing adapt permission.

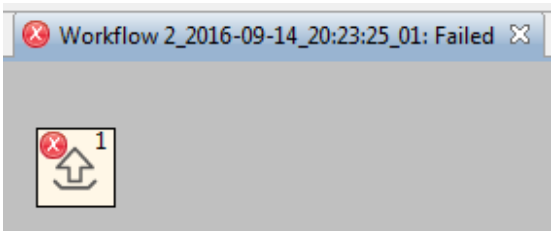
Test case 2

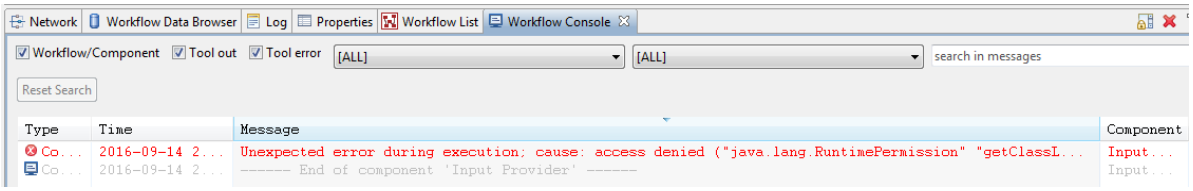
Description: Workflow 2 is executed on the server instance and the client instance executes the Input Provider component.



Expected results: The Input Provider has access to the "input" file and thus, it requests a read file permission on the client instance. The workflow finishes without an error.

Actual results:





Evaluation: A permission request dialog is prompted for the Input Provider component. However, the workflow fails, because a runtime permission is missing.

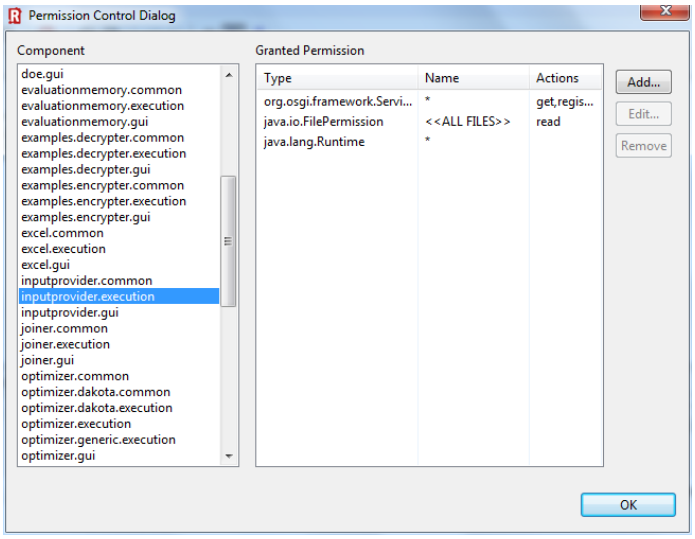
Test case 3

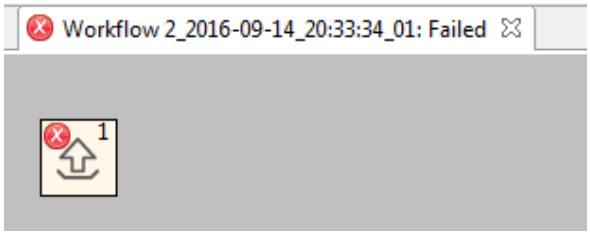
Description: The RCE client instance is restarted and the Input Provider component is granted with full file and runtime permission. Afterwards, Workflow 2 is executed on the server and the component on the client.

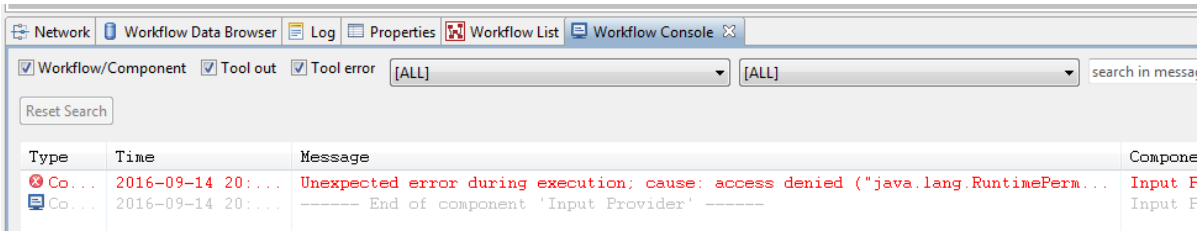
Expected results: The workflow executes without asking for a missing permission.

Actual results:

Evaluation: The workflow did not request the file permission. However, the workflow fails with a missing runtime permission. Even the runtime permission is explicitly granted to the component.







Test suite 3

Description

The test suite evaluates the effects of the sandbox prototype in RCE on the user experience of executing workflows. The number of permission request dialogs is counted in each test case. For evaluation purposes workflows are executed on a single RCE instance. The test cases describe the execution of the following workflows:

Workflow 1 contains one *Input Provider* component. The Input Provider provides outputs for other components with different data types such as integer, boolean and file. A file output is configured for the component. Workflow 2 contains one *Script* component. A script can be programmed and executed with Python or Jython. A script is programmed to display a string in the RCE console.

Precondition

1. A RCE instance is started with active sandbox.
2. A new project is created.
3. A text file called "input" is created with the content "RCE sandbox".

4. A new workflow called "Workflow 1" is created with a *Input Provider* component and the "Input" file is configured as output.
5. A new workflow called "Workflow 2" is created with a *Script* component and the script displays the string "Hello World".
6. The administrator does not provide additional permissions for the components.

Test case 1

Description: Workflow 1 is executed. All permission requests are granted permanently and the appearing dialogs are counted.

Expected results: Input Provider requires a file permission access. One permission request dialog is prompted and is accepted permanently. The workflow finished without prompting a dialog again.

Expected number of dialogs: 1

Actual results: Actual number of dialogs: 1

Evaluation: The workflow is finished with prompting one dialog. The actual number of dialogs is correct.

Test case 2

Description: Workflow 1 is executed after the RCE instance is restarted. All permission requests are granted temporarily and the appearing dialogs are counted.

Expected results: Input Provider requires a file permission access. All appearing dialogs are granted temporarily. Hence, the workflow may produce several permission request dialogs before finishing.

Expected number of dialogs: 1 or more

Actual results: Actual number of dialogs: 4

Evaluation: The Input Provider must access the file four times. Therefore, the dialog appears four times, because granting temporarily is only valid for one access.

Test case 3

Description: The administrator grants full file access to the Input Provider. Workflow 1 is executed.

Expected results: The workflow executes without prompting a permission request dialog. Input Provider is already granted with the file permission.

Expected number of dialogs: 0

Actual results: Actual number of dialogs: 0

Evaluation: The workflow executes without prompting one dialog.

Test case 4

Description: Jython is selected as script language and Workflow 2 is executed. All permission requests are granted permanently and the appearing dialogs are counted.

Expected results: The Script component requests 7 different permissions and each is granted permanently.

Expected number of dialogs: 7

Actual results: Actual number of dialogs: 7

Evaluation: The workflow is finished with prompting one dialog. The actual number of dialogs is correct.

Test case 5

Description: Workflow 1 is executed after the RCE instance is restarted. Jython is still used for executing the script. All permission requests are granted temporarily and the appearing dialogs are counted.

Expected results: The Script component already accesses 7 different permissions. Each corresponding resource may be accessed several times. Hence, the dialog may be requested more than 7 times.

Expected number of dialogs: 7 or more

Actual results: Actual number of dialogs: more than 100

Evaluation: The actual number of dialogs indicate that the Script component performs a lot of accesses to protected resources like file access.